Non-Invasive and Cost Effective Monitoring of Energy Consumption Patterns for Electrical Equipment

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Abstract
Electricity use in many buildings is increasing, sometimes such that new buildings built to modern standards can have greater energy usage than their predecessors. A major cause is increased use of appliances such as computer equipment, lighting, and electronics. Increasing standby power consumption and more appliances being left running unnecessarily, compounds these effects. Monitoring equipment should provide insights into these issues, but the few systems currently available are either expensive, invasive, or both. This paper shows a case study where temperature monitoring was used to reduce industrial plant usage, and shows a method of electrical appliance monitoring, using very low cost sensors. Results show that the method can effectively reveal equipment usage patterns.

Nomenclature

b	filter coefficients (unitless)
Gt	temperature gradient (unitless)
H	filter transfer function (unitless)
N	filter order (unitless)
Ta	ambient temperature (^oC)
To	max. operating temperature (^oC)
Tp	instantaneous temperature (^oC)
Ts	standby temperature (^oC)
Z	z transform operator (unitless)
CT	current transformer
LDR	light dependent resistor
OCR	optical character recognition
OMR	optical meter reader

Introduction
Buildings account for almost 50% of C02 emissons in the UK [1]. As part of the Carbon Reduction in Buildings Project, the authors investigated new ways of analysing half-hourly data at the appliance level [2], noting a scarcity of suitable appliance monitoring systems. While plug in power meters provide a basic audit of appliances, usage patterns are not established, since the power meters do not log. Energy use questionnaires have worked well, but discrepancies may exist between perception of energy use and reality [3].

Non-invasive sensing
The key concept described in this paper is the use of non-invasive temperature sensing for appliance usage patterns. While temperature logging of plant has been carried out in the past to determine machinery ‘health’, for example lubricating oil temperatures in HVAC plant, we propose a more wide ranging strategy of temperature monitoring for tens or even hundreds of electrical appliances within a building, in order to build a complete picture of electrical energy consumption. We also propose a method of data post processing which produces easily identifiable duty cycles as opposed to raw temperature data. As a result, the data is readily processable by software, which becomes crucial for large audits, for example of all IT hardware within an office block. The method is low cost. A further advantage of case temperature monitoring is that personnel carrying out energy audits do not need to remove equipment covers, or work with high voltage cabling.

Whole system (building) monitoring
Energy meters can be read manually for patterns of overall appliance use, which is entirely non-invasive and usually very reliable, provided the readings actually occur. But this is not practical for high frequency (<hourly) readings. For automatic logging, some energy meters may give a contact closure, or increasingly commonly, a solid state output. The connection usually takes the form of an RJ10 connector, similar to a UK telephone plug [4]. Where a pulse output meter is fitted, logging is theoretically easy. However, energy suppliers’ permission to utilise UK energy meter electrical pulses is required. Noting the complicated structure of UK energy supply, dialogue with energy companies is difficult, therefore non-contact sensing data collection being magnetic or optical, or recently, OCR based. Where possible, the simplest option is to utilise a meter which produces a magnetic pulse.

The meter casing remains un-breached, and therefore maintains compliance with ingress protection standards for electricity meters. An OMR [5] uses a send and receive pair of photodiodes, to view the passage of analogue dial pointers, e.g. from the revolving disk of an electricity meter. A pulse logger stores in memory the number of meter pulses for a given time period. The authors have developed a solution for pulse logging where electricity meters feature a flashing LED. A NORPS-12 type LDR, is able to provide an output which directly drives a small pulse logger [6]. This provides a compact solution for pulse counting over a programmable interval, with a storage capacity for half hourly metering of around 400 days. CTs may be used to detect power consumption, the proviso being that a clear phase is required for sensing (multicore Live Neutral and Earth cable, for example, would not be suitable). Another disadvantage of CT based devices is poor sensitivity for low loads.

Individual appliance monitoring

Appliance monitoring systems differ from plug in power meters in that logging is possible. The Watteco, relied on deciphering circuit behaviour [7] although current trends suggest that powerline communications [8] may prove more reliable. Such systems can produce very high quality data, but may not be required for a basic energy audit. Another method of measuring appliance usage may involve sense the magnetic field of a motor or flourescent ballast [9]. It is fundamental that in the majority of cases, an electrical appliance will become warm through normal use. Main causes of this may be due to electrical inefficiences (such as heat generated by electronics), magnetic circuits (eddy current heating of transformer cores), deliberate heating (e.g. a cathode ray tube or heating element), or process heat (e.g. a washing machine or airconditioner). Measurement of case temperatures provides a low cost method of usage pattern monitoring. A summary of the available technologies for individual appliance monitoring is provided below in Table 1.

Table 1 – Summary of technologies for appliance monitoring

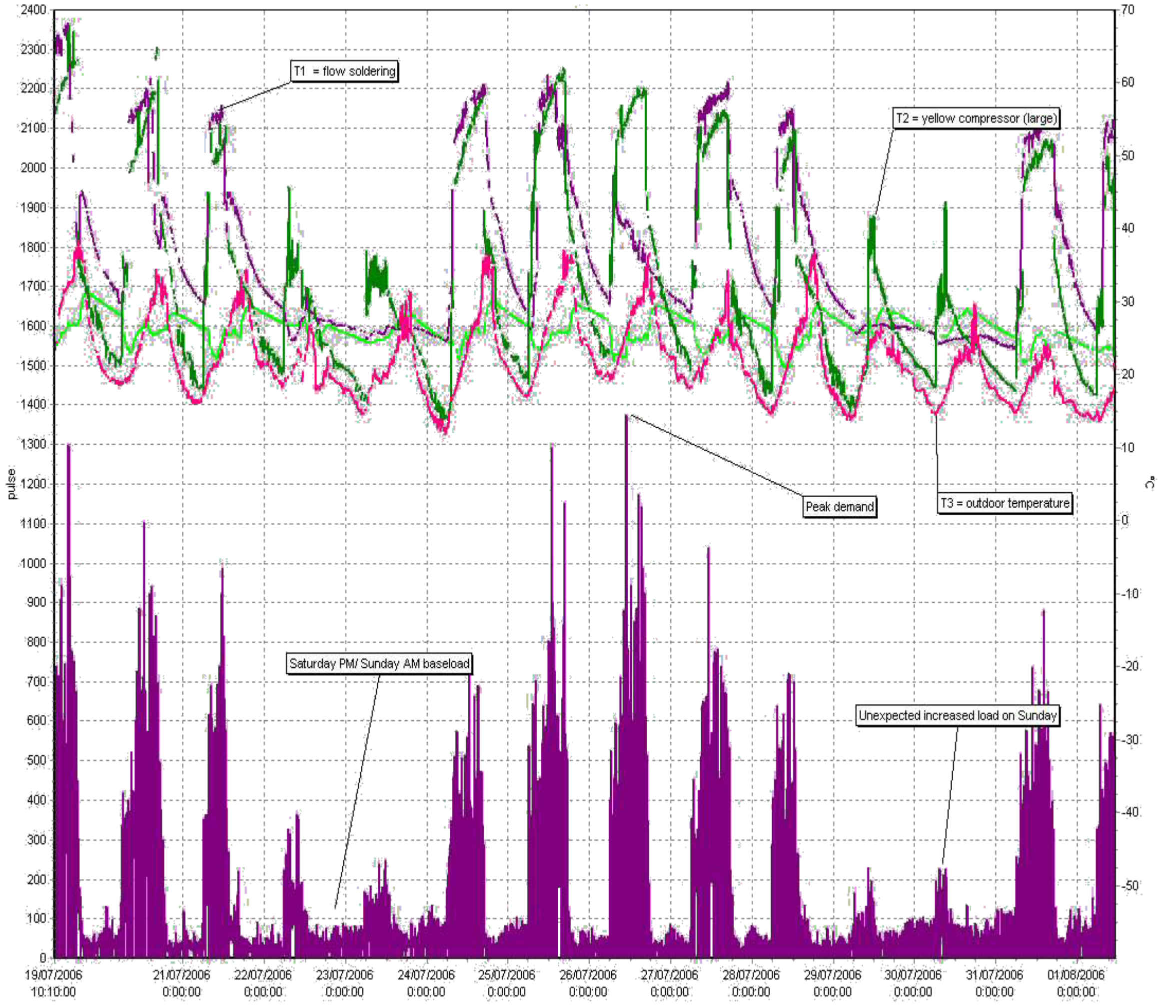
Technology	Approx. Base cost for hardware, software. (Euro)	Approx. Cost (Euro) per appliance	Notes
Temperature loggers	50	25	Imprecise, post processing needed
Power meters (plug in)	0	25	Not capable of profile logging but capable of measuring integrated consumption
Power meters (benchtop)	25	300	Bulky – lab apparatus used for calibration but capable of logging and very accurate
Current clamps	40	150	Manual data collection required, certain current transformers may not operate at low currents
Magnetic field sensor	25	60	Needs to be positioned close to motor or flourescent light ballast
Individual appliance monitoring	1000	120	Extremely accurate and precise, automatic data uploads include integrated consumption

Case Study – non-invasive industrial forensic monitoring using case temperatures

The East Midlands New Technology Initiative (NTI) in the UK, is backed by leading colleges and universities in the region. NTI provides grants to small and medium sized businesses to invest in state of the art technology and gain advanced technology skills through NTI approved courses. As part of this work, an electronics factory was visited in order to carry out forensic plant monitoring. The factory is an SME, employing around 40 staff (Figure 1, figure 2), and is occupied from Monday to Friday for production, although some administration occurs on Saturdays. Using an Eltek radio datalogging system, two items of plant were tested, a flow soldering machine (figure 3), and an air compressor located outside, shown in figure 4, probes clipped to hot air exhausts for each item. Data was logged at 5 minute intervals for 14 days. A Willow optical meter reader was used to monitor electricity consumption from the main site electricity meter. As can be seen from figure 5, the temperature of the flow soldering machine (the largest item of plant at the factory) approximately correlates with overall electrical load. (Th2 is ambient indoor temperature). During the investigation, this machine was the subject of an energy management strategy, and was timed to preheat shortly before the start of each shift. A 24 hour time switch supplied the compressor to switch off at night. As can be seen from the plot, compressor temperature clearly indicates weekend running, where the compressor ran due to system leakage. As well as tackling air system leaks, the compressor timer was changed to prevent weekend operation. This shows an example of a simple application of temperature monitoring for identification of plant usage, with energy savings.

Figure 1 – Factory Exterior 	Figure 2 – Factory interior 
Figure 3 – Flow Soldering Machine Exhaust 	Figure 4 – Compressor Hot Air Exhaust 

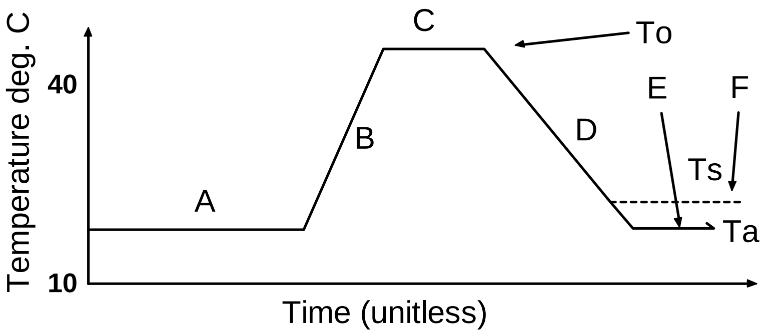
Figure 5 - Factory plant case temperatures and overall factory electricity consumption



Data post processing

Thresholding of temperature data, either by sight or using automated methods, is effective in producing a rough estimate of appliance usage, but cannot compete with direct power measurement for precise appliance use estimation. Subtraction of ambient temperatures may assist in improving the reliability of thresholding, but its use is limited, since appliances with a high thermal mass may never cool enough when switched off to cross the threshold. An alternative approach which should produce more accurate data is to look at the heating/cooling cycle. Case temperature of an electrical appliance typically follows a set pattern. Referring to figure 6, when the appliance is at rest, case temperature equals ambient (A). When power is applied, case temperature rises (B) until a maximum is reached. Unless varying loads are present (e.g. for a washing machine, computer), operating temperature (T_o) is typically steady. When power is disconnected, case temperature will drop back to ambient, the slope (D) usually being less than that of B. The case temperature will then return to ambient (E). If an appliance is left on standby, the small power drain will usually affect case temperature, such that the standby temperature (T_s) will be several degrees above ambient. In reality, some post processing must be applied for precise, automatic analysis. The intention is to produce a stream of binary data, reflecting appliance 'on' and 'off' times.

Figure 6 – profile of case temperature for electrical appliance



We can use the measurement of the first differential to detect events ABC and D (1).

$$G_t = \Delta T_p / \Delta t \qquad (1)$$

Where temperature sensors of low precision are used, quantization may produce false events. A moving average filter may be applied to assist in visualisation. In mathematics and signal processing, the Z-transform converts a discrete time-domain signal, which is a sequence of real or complex numbers, into a complex frequency-domain representation [11]. The filter coefficients are found via (2). Taking a filter order of 2 for example, we can produce a low pass filter (3).

$$b_i = \frac{1}{N+1} \quad \text{for } I = 0,1,\ldots,N \qquad (2)$$

$$H(z) = \frac{1}{3} + \frac{1}{3}z^{-1} + \frac{1}{3}z^{-2} = \frac{1}{3}\frac{z^2+z+1}{z^2} \qquad (3)$$

Experimental setup

Referring to figure 7, a Hameg HM8115-2 power meter (1) was used to measure the power consumption of a small (500W) electric heater (2). The Hameg meter has 100mW precision and +/- 0.5% accuracy. A Thermochron iButton sensor type DS1921G-F50 was used to monitor case temperature (3), shown in more detail in figure 8, the sensors costing around 25 Euros. A Hameg HZ815 mains breakout box (4), was used to interface between the power meter and heater. Results were recorded on a laptop (5), and ambient temperature was also recorded (6). A mains timer plug was used to cycle the heater at fixed intervals. The iButtons logged at 1 minute intervals (shortest available) and the Hameg system at 10 seconds.

Figure 7 – experimental setup

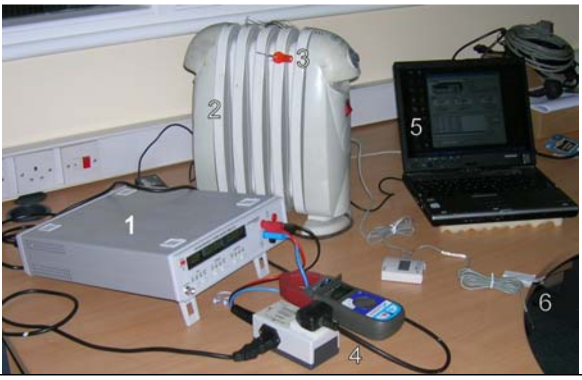


Figure 8 – Thermochron iButton

Results

Figure 9 shows the temperature variation over time for the heater test as outlined in the previous section – overlayed is the first differential of temperature, showing more clearly the effects of quantisation. Figure 10 (upper), shows the actual measured power for the heater. Duty cycles are inferred in Figure 10 (lower) using a basic algorithm, whereby a positive slope represents ‘on’ and a negative slope represents ‘off’, i.e. steps B and D as outlined in Figure 2.

Figure 11 (upper) shows the effect of an improved algorithm with steady state conditions for on and off. For each temperature point, the algorithm checks the previous reading. If the slope is positive, state B is assumed, and if the slope is negative, state D is assumed. A two stage check is made for states A and C, whereby in each condition the slope must be zero to remain in steady state, with a check against the previous reading to establish whether this steady state is on or off.

Figure 11 (lower) shows the effect of using this improved algorithm as well as cleaning the original signal with a low pass filter as described in the previous section. A fourth order filter is used, implemented as a convolution filter using a filter array of [1 1 1 1]. As can be seen, the false 'off' event has been removed, and the duty signal follows a pattern of general lag behind the applied power which would be as expected. The precision of sensing appliance duties is summarised in Table 2.

Figure 9 – Temperature Plot from Experiment and First Differential

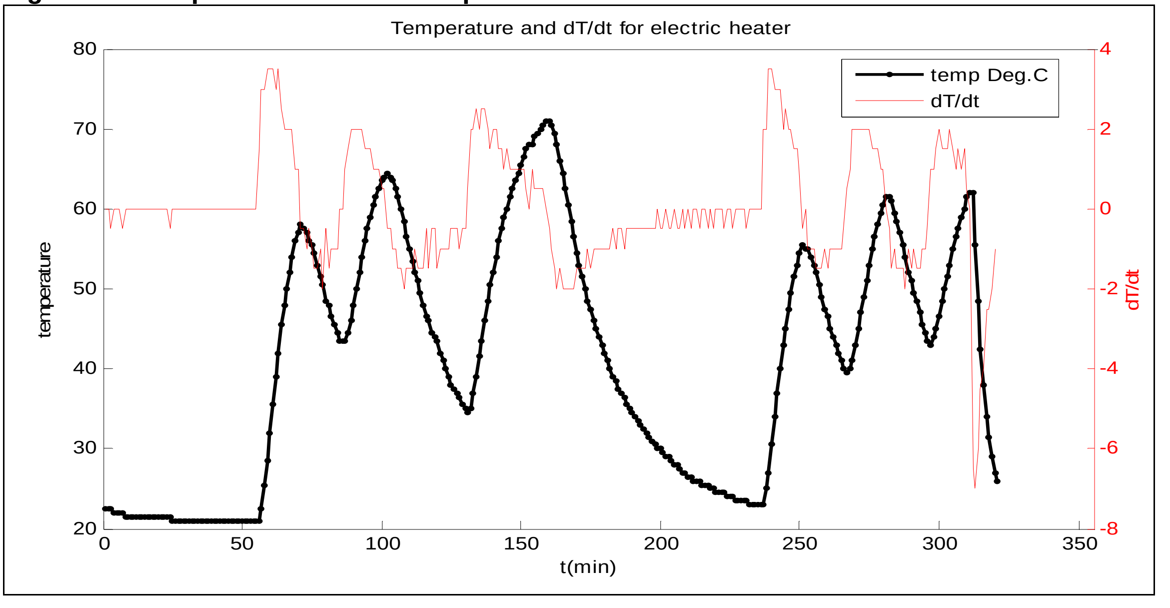


Figure 10 – Actual Power Consumption and Inferred Duty Cycles for Electric Heater

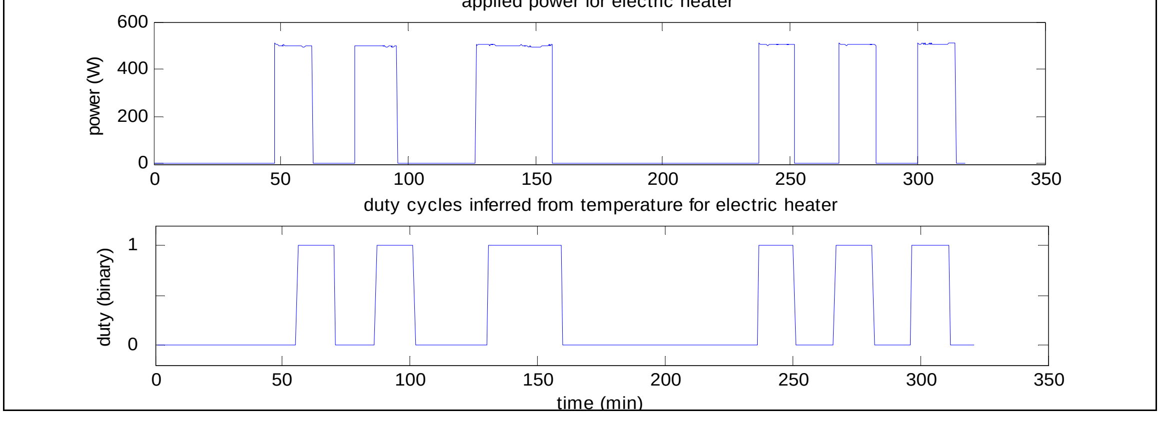


Figure 11 – improved sensing algorithm and effect of low pass filtering

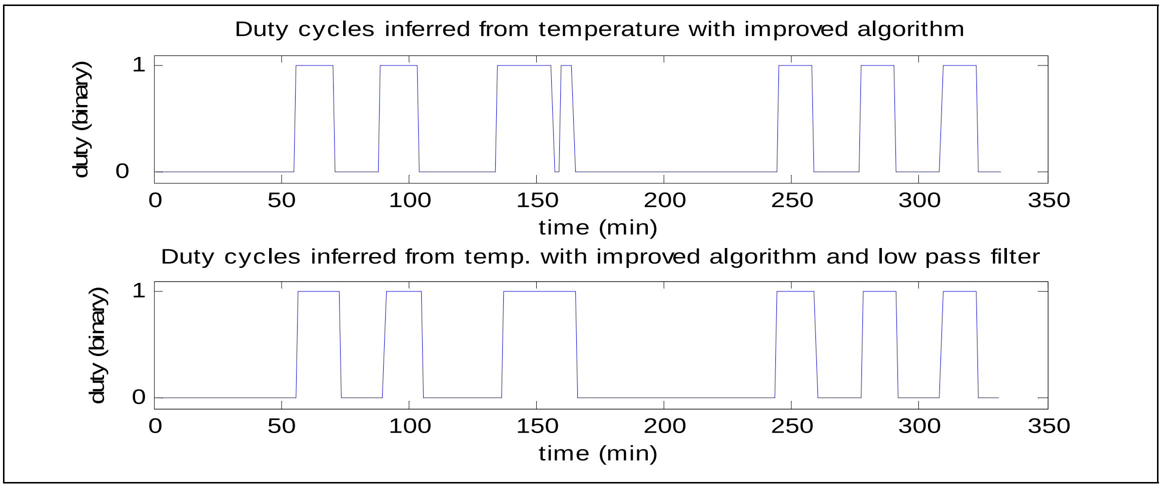


Table 2 – results summary

	Duty	Accuracy
Measured directly from power consumption	0.3267	100%
ABCD temperature based detection	0.2982	91%
ABCD temperature plus low pass filter	0.3127	97.09%

Discussion

Referring to figure 10, no provision for steps A and C as shown in figure 6, has been included in the original processing algorithm, which would lead to false readings should T_p remain in either fixed 'on' or 'off' positions, with small variations in temperature caused by power variation or ambient. These small increases or drops in slope would cause erroneous switching events to be reported. An interesting further side effect is the apparent 'phase lead' where temperature changes apparently occur ahead of the appliance being switched on, which is clearly visible in the inferred temperature cycles plot shown in figure 10, after 240 min. This is caused by the lack of a 'steady state' condition to the algorithm, whilst the general underlying temperature trend is increasing.

Figure 11 shows that the effect of improving the algorithm is clear, with a phase lag for duty following temperature as expected. A degree of phase lag is of course inevitable for this sensing method. However, an event at around 155 minutes into the test has caused a false 'off' reading. Examination of figure 9 shows clearly how quantisation has affected the data, i.e. the temperature sensor 'shuttering' between the two closest measurement values which it was able to register. Given the long time constant of the heater, the sample rate far exceeds the maximum frequency of interest according to the Nyquist Criterion. A low pass filter therefore may not degrade the information contained in the temperature data significantly, yet could improve the quality of results. Table 2 shows the accuracy of using temperature profiles to predict the duty (usage) of the heating appliance under test. The results show that the use of a low pass filter has improved post processing performance, with an encouraging result, very close to the value obtained from direct power logging.

Conclusions

This work has demonstrated that this method of non-invasive low cost monitoring can assist greatly in establishing patterns of plant use and hence, reducing energy consumption. In a 'real world' test, we have described the detection of factory plant, in this case an air compressor, running unnecessarily at weekends. In addition, we have described a method of analysis of temperature data from an appliance in the laboratory, which would not produce meaningful results with simple thresholding due to the pattern of use employed. This has demonstrated that very low cost temperature sensors are useful for appliance and plant monitoring, at a fraction of the cost of conventional methods. The non-invasive nature of fitting means that auditors do not need to remove equipment covers (as is often the case with current transformers), and installation of monitoring equipment is very rapid. This approach of minimal disturbance is especially important when ensuring cooperation of building occupants in monitoring projects, for example in offices.

We have explored post processing methods to produce meaningful information from the raw temperature data. Experimental results have shown that an accuracy of over 97% was achievable when estimating the duty cycle of the appliance using low cost temperature loggers.

Acknowledgments

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References

1. DEFRA, DEFRA, e-Digest Statistics about: Climate Change. 2006.
http://www.defra.gov.uk/environment/statistics/globatmos/
DEFRA Customer Contact Unit, Eastbury House, 30 - 34 Albert Embankment, London, SE1 7TL, UK
2. Brown, N., Wright, A.J., New Approaches to the Gathering, Analysis and Interpretation of Half Hourly Energy Metering Data from Buildings. International Journal of Low Carbon Technologies (IJLCT), Volume 2, Issue 1, Jan 2007
3. Wall, R. and Crosbie, T. (2007). A socio-technical analysis of domestic lighting use: what's wrong with energy-efficient lighting? 7th Biennial Conference on Environmental Psychology, University of Bayreuth, Germany, September 10-12.
4. BSI, 'EN 62053-61:1998 Electricity metering equipment (a.c.) —Particular requirements' British Standards Institution, Technical Indexes Limited, Willoughby Road, Bracknell, Berkshire, RG12 8DW, UK (1999).
5. Anonymous, 'Willow Optical Meter Reader, Technical Data' http://www.elcomponent.co.uk/ Elcomponent Ltd, Southmill Trading Centre, Bishop's Stortford, Hertfordshire, CM23 3DY, U.K. (2006).
6. Anonymous, 'Madgetech Pulse 101 Pulse Logger Technical Data' http://www.madgetech.com/ MadgeTech, Inc. PO Box 50 201 Route 103 West Warner, NH 03278 U.S.A (2006).
7. Bertrand, P., Method and apparatus for measuring the consumption of an element of an electrical network, in European Patent Office. 2001, Conseil En Technologies Innova: France.
8. Anonymous, Digital Living Ltd Website, http://www.digitalliving.ltd.uk/, 101 High Street, Wallingford, OX10 0BL, UK.
9. Anonymous. U9 Series Motor on/off logger technical data. Tempcon Instrumentation Ltd.
Unit 19 Ford Lane Business Park Ford Lane Ford Nr. Arundel West Sussex BN18 0UZ, UK http://www.tempcon.co.uk/
10. Anonymous. NTI Website. East Midlands NTI Ltd, The Innovation Centre, 49 Oxford Street, Leicester, LE1 5XY. http://www.eastmidlandsnti.co.uk
11. Oppenheim, A.V., Schafer, R.W. Digital Signal Processing, Prentice Hall, ISBN 0132146355