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Andrew R. Pollard

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The Measurement of Whole Building Energy Usage for New Zealand Houses

A R Pollard*, B.Sc.(Hons), MNZIP, MANZSES

The Household Energy End-Use Project (HEEP) seeks to create a model of energy end-use for New Zealand houses. Measuring the energy usage down to end-use levels in a large number of houses is not possible due to the high cost involved. The HEEP project therefore includes monitoring of whole building energy use which allows for a statistically significant number of houses to be measured. This paper comments on the measurement methods and there uncertainties used for the collection of whole building energy data from New Zealand houses.

***Keywords**: Energy Measurement, Energy End-Use, Gas Measurement.*

* *Building Physicist, Building Research Association of New Zealand (BRANZ), Private Bag 50908, Porirua, Email: branzarp@branz.org.nz*

1. Introduction

In 1997 the residential sector used 13% of the total energy and 35% of the electricity consumed in New Zealand[1]. Residential energy consumption is predicted to grow by 1.7% pa to 2020. A total of 2600 MW of additional electricity capacity[2] is expected to be economic by 2020. An understanding of demand is important. In the 1970's large increases in capacity were seen[3] to be required in the Pacific Northwest region of the United States of America. As a result the Washington Public Power Supply System began construction of five nuclear power plants. By 1984 when the large increase in demand had not eventuated, construction of two of these plants were terminated and another two were mothballed at the cost of several billion dollars. Learning from this, a large measurement campaign (ELCAP[4]) was undertaken by the Bonneville Power Administration to improve understanding of demand in this region.

Information on demand in the residential sector in New Zealand has been limited since the 1971/72 Survey of Household Electricity Consumption[5,6]. The common use of 'rules of thumb' in energy demand prediction has resulted in high uncertainty in the estimates of future energy demand. The Household Energy End-Use Project (HEEP)[7,8,9] was initiated to provide more certainty in the future demands of energy use in New Zealand's residential sector. While certainty of energy supply and the cost of electricity are topical issues at the moment, an understanding of the underlying demand is crucial.

In seeking to conserve future energy use, it is wise to consider the methods used to measure and verify energy savings. The International Performance Measurement and Verification Protocol (IPMVP)[10] is a widely accepted guideline to follow. An emphasis of the IPMVP is on good quality measurement. Measurement is a component of the much broader concept of monitoring. To quote from Chapter 37 of ASHRAE's HVAC Applications[11]: '*The key issues in monitoring are the accuracy and reliability of the data*.' It is for this reason that careful attention is paid to the monitoring for HEEP. This paper examines the energy measurements considered useful and then investigates the quality of the measurements and in particular the methods to account for gas usage.

2. Methodology

The output of HEEP will be a model of energy end-use in New Zealand residential buildings. In order to develop this model it is necessary to monitor energy in order to understand how it is used. Monitoring of energy end-use can take a variety of forms. 'Static' information is collected in the form of a survey and covers topics such as occupant attitudes, behaviour and socio-demographics, appliance ownership and characteristics of the building. Changing 'static' information can be a useful method to examine the impact of those factors. In the Twin Rivers Study, Sonderegger[12] was able to examine the effects the occupants had on the energy consumption of the building by comparing energy use in houses that had a change of occupants with houses that did not have a change of occupants.

To validate the data, measurements of 'dynamic' energy end-use are also required. The cost of measuring energy use within buildings is a non-linear function of the sample size[11]. In order to gather sufficient variety of social parameters, a large number of houses will need to be measured. Methods are being established to make best use of the information collected. For HEEP two types of measurements are undertaken; Energy End-Use Measurement which records the energy consumption down to individual end-uses (Hot Water, Lighting, Heating, Cooking, etc.); and Whole Building Energy Measurement which measures the various energy flows into the building. Where possible the Whole Building Energy Measurement also includes the measurement of large energy end-uses such as water heating.

The experimental method for HEEP is intended to involve the measuring of energy use in at least 400 houses throughout the country. With eleven sets of end-use measuring equipment available, it is anticipated that 55 houses will be able to be measured at the end-use level over the five years of measurements. The remaining 345 houses will be monitored at the whole building energy level.

3. Analysis of Data

There are two types of measurements available from the data loggers: consumption measurements of energy use and instantaneous measurements of variables such as temperature and humidity. The instantaneous measurements are independent of the time interval used. As consumption is dependent on time, the consumption measurements will change with different time intervals. It is desirable to be able to compare two time-series of different intervals without consideration to what time interval is used for the time-series. The time-series are consequently constructed from power information obtained by dividing the energy consumed in the interval by the time of that interval. By convention the time attached to the measurement is the time at the start of the period of consumption.

The length of the interval used in the time-series is subject to debate. While it is possible to aggregate the data by adding together a number of separate intervals to produce broader based data, it is rarely possible to reliably break down consumption for long periods into shorter periods. The use of longer intervals has the effect of averaging out the different events making up the consumption. A time-series constructed with a short interval reveals more information on the nature of the energy usage within the house. FIGURE 1 shows four time-series of the same one minute data aggregated to intervals of one, five, ten and thirty minute intervals. It is seen that the one minute profile contains considerably more information on energy usage within the house than the thirty minute profile. Shorter intervals have the drawback of requiring more storage space for the data, however as the cost storage reduces this will begin to become less of a concern.

With the use of shorter and shorter intervals the effects of individual appliances can be more readily seen within the total load profiles. Individual appliances can be seen to switch on and off at particular times. It is not unreasonable to expect that if a sufficiently short interval was used and the switching characteristics of a number of appliances were known then additional information as to when these individual appliances were on may be inferred from the total load profile. This "end-use disagregation" is being investigated for use in the HEEP project. There are meters available that are capable of recognising the step changes associated with appliances switching on[13,14], however these overseas-developed systems are still at an early stage of development and are not easily adaptable to New Zealand conditions. The analysis for total load profiles for HEEP will make use of surveyed information that will assist with apportioning the energy to separate appliances.

Depending on the fuel type being examined an interval can get too short. This is a consequence of the resolution of the energy measurement for the fuel type and the typical demand of that energy. With the electricity measurements being of good resolution and of constant measurable demand, electricity is generally well behaved.

The measurement of gas however can have problems due to metering constraints. For LPG the resolution of the energy measurement is approximately 0.35 kWh (gross calorific value 118 MJ/m^3, a regulator setting of 7 kPa gauge and neglecting other factors). Portable LPG heaters generally have three output settings between 1 kW and 4 kW. An LPG heater operating at 1 kW will register non-zero data once every 20 minutes. Data for LPG heaters therefore needs to be analysed on a longer time interval to account for this lack of energy resolution. The resolution of natural gas is much better with a resolution of approximately 0.12 kWh (gross calorific value of 41 MJ/m^3, a pressure regulator setting of 3 kPa gauge and neglecting other factors). Natural Gas measurement can still cause problems when more than one end-use is being measured. When the energy use of a gas appliance is inferred from the measurement of the total gas usage for the house less the measurement of gas usage for all other appliances negative values may occur. These negative values are a result of the meters operating in a constantly integrating mode with the consumption registers in the meters not being synchronised at the start of each interval. The largest number of negative pulses that can be registered is one less than the number of meters used. The solution to this problem is again to consider a longer analysis interval.

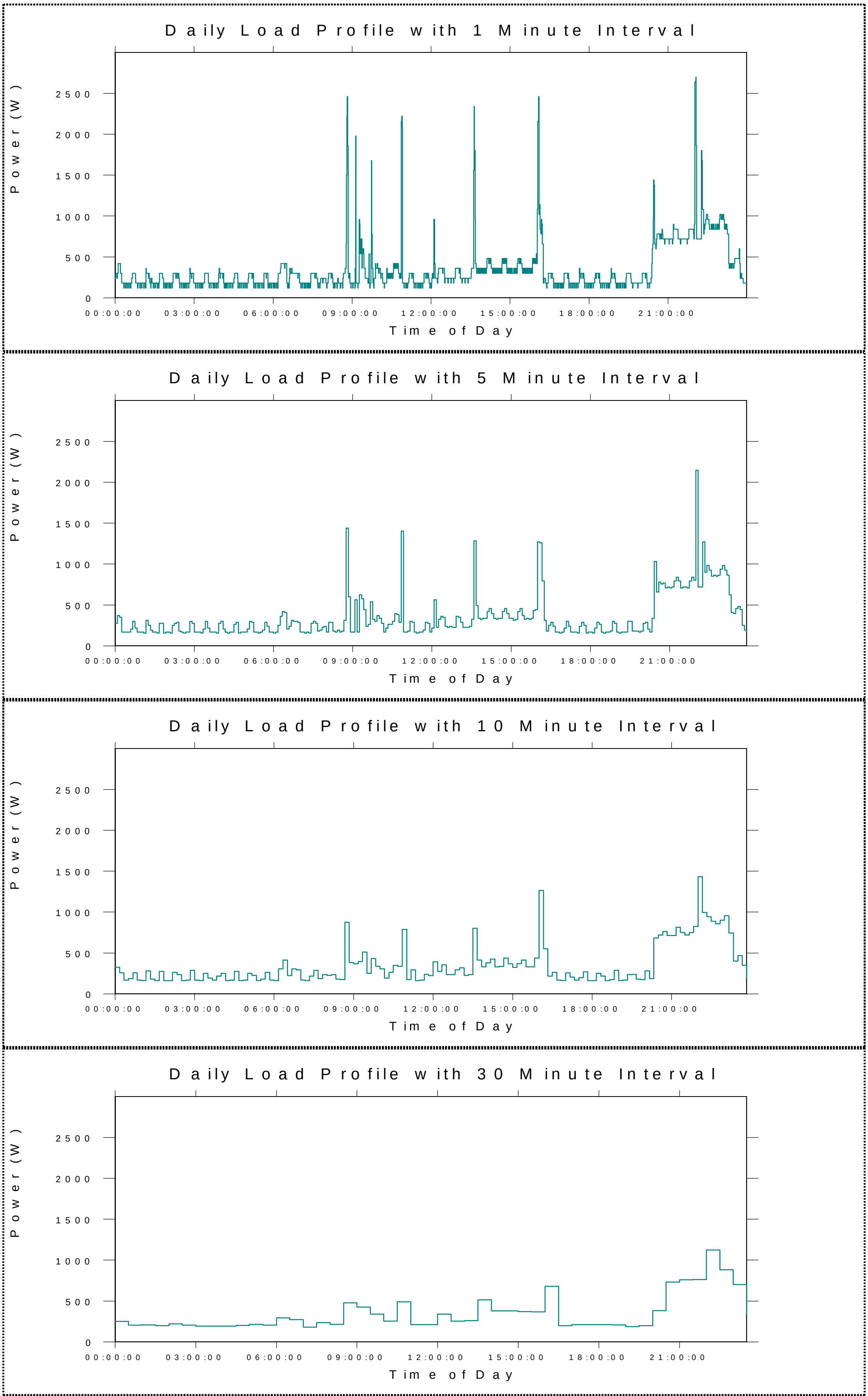

FIGURE 1: Energy profiles of the same energy consumption with varying aggregation intervals.

The HEEP database is set-up to a ten minute interval. Data from the loggers are aggregated from one and two minute intervals to ten minutes. End-use extraction will need to be undertaken on the raw, one and two minute data with the ten minute end-use estimates being input into the HEEP database. With there being a variety of accuracy for data in the HEEP database, estimates of data accuracy would be useful to include within the database structure. With many determinants of energy use having a daily frequency (for example, the temperature) an important analysis time interval is daily consumption information. Daily information will be the basis on which seasonal effects will be seen in the data.

3. Data Collection

Any data collection system makes an impact on the occupants of the house. In order to minimise this impact for the HEEP project cabling is kept to a minimum. The measurement of total electrical, reticulated natural gas and liquefied petroleum gas (LPG) usage within a building is achieved in the HEEP project with a separation between the sensor and the data capture and storage device (data logger). A consequence of this is that there is no central logging point within the house but instead each logger is independent. Modem communications are therefore not possible and regular visits are required to the house to off-load data.

3.1 Sensors

The sensors used for measuring electricity and gas are consumption sensors (energy for electricity and volume for gas) as opposed to rate-of-consumption sensors (power for electricity and flow for gas). The output of the consumption sensor is a pulse for each marginal unit of consumption. There is no time setting required as this is undertaken by the data capture device connect to the sensor. Data capture is discussed in section 3.2.

The sensor used to monitor electrical energy in houses is a static (solid state) watt-hour meter, as used by many power companies. The particular meter is a single phase Siemens S2A100S meter. These meters are manufactured in large quantities and consequently the meter is cheaper than dedicated kilowatt-hour transducers. The pulse output of the Siemens meter has a resolution of 0.001 kWh and complies with the requirements of the IEC61036[15] accuracy class 2. For currents between 2 A and 80 A the meter will read within ± 2% of the true energy consumption when used at 23 °C. This meter also incorporates a logging capacity, however, it is limited to half-hour intervals and is capable of only storing one week's duration of data and thus is not suitable for other than basic monitoring tasks. The Siemens meter is installed on the meter board immediately following the power company's meter. The small size of the Siemens meter (145 mm x 100 mm x 55 mm) frequently allows additional Siemens meters to be installed on the meterboard allowing additional large loads (such as the hot water cylinder) to be monitored. As the current sample region is largely urban (Wellington, Lower Hutt, Upper Hutt and Porirua City Council areas) there has not been a great need to monitor houses supplied with multi-phase electricity.

The measurement of reticulated gas involves interrupting the gas pipes to the house or to individual appliances to install Gallus 2000 G2.5 gas flow meters. The Gallus 2000 G2.5 is a standard tariff meter as used for the supply of natural gas to households. The Gallus meters have been fitted with a pulsed output providing a pulse for each 0.01 m^3 of gas delivered. The volume of gas delivered by the Gallus meter for flows between 0.03 m^3/hr and 4.0 m^3/hr is within a range of ± 1.5% of the reading. This range corresponds to a standard uncertainty[16] in the volume measurement of 0.9% of the reading.† The installation of additional gas meters within existing pipework can be an awkward and expensive task. The physical size of the meters (280 mm x 220 mm x 180 mm) restricts locations where the meters can be placed within the house

The use of bottled LPG gas in New Zealand is considerable. There are approximately four hundred thousand portable LPG heaters in New Zealand[17]. For the measurement of bottled LPG usage, the Gallus meter is also used. For portable LPG heaters these meters are mounted on a board protruding from the back of the heater extending the depth of the heater by about 250 mm.

3.2 Data Capture and Storage

The output of the electricity and gas sensors are pulse signals. Pulse signals are easy to process as they can be converted into the digital domain easily. The logger used to capture and store the consumption information is a BRANZ pulse logger. The emphasis with these loggers was to develop a data collector specifically for this application rather than to develop a general purpose logger. By limiting the

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† The standard uncertainty of a variable with a rectangular distribution of half-width a is $a/\sqrt{3}$

flexibility of the logger it has been possible to extend many of the features compared with general purpose loggers.

As the HEEP database is set-up as an evenly spaced time-series, the number of pulses occurring within a pre-set interval is the basis of the stored information rather than the time between pulse events (such as recording the time between consecutive pulses). Up to four channels of pulse inputs can be recorded by the logger with each channel capable of recording 254 pulses per logging interval. This limitation of 254 pulses requires that the logging time interval is selected small enough to allow the storage of the power being monitored. For electricity the maximum energy that can be recorded in each interval is 0.254 kWh. When a 1-minute interval is used the maximum power that can be monitored is 15.3 kW and when a 2-minute interval is used the maximum power is halved to 7.65 kW. For gas, the greatest volume of gas that can be measured within an interval is 2.54 m^3. Consequently, the largest energy that can be recorded for an individual reading is approximately 29 kWh (104 MJ) for natural gas and 83 kWh (298 MJ) for LPG (the calorific values in Section 4.3.1 have been used).

The BRANZ pulse logger has 64k of memory providing storage for approximately 59000 readings. The length of time before the memory becomes full depends on the number of channels logged and time interval of the channels. For the HEEP monitoring, it is intended that the loggers be off-loaded on a monthly basis. The two modes used for the HEEP monitoring are 1-channel, 1-minute logging and 2-channel, 2-minute logging. Both these modes set the logger storage capacity to approximately 41 days.

3.3 Other Measurements

The HEEP data collection also needs to account for the energy used in solid fuel appliances such as enclosed wood burners, open fires, coal burners and other such appliances. The number of dynamic parameters determining the energy output of solid fuel appliances is large. It is difficult to control or monitor many of these parameters outside the laboratory. The estimation of solid fuel energy therefore has a larger uncertainty than the other fuel types.

The data collected on solid fuel includes information on the type of fuel loaded into the burner as well as measurements of surface temperatures of the burner. The occupants are asked to fill out a notebook when they use the burner. This notebook identifies the type and amount of fuel used as well as comments such as damper settings on the appliance. The surface temperatures of the burner is recorded by a temperature data logger and provides an indication of how much heat is being delivered to the room.

With space-heating being a large contribution to the energy use in New Zealand houses[18] additional information that adds to the understanding of space heating is important. An important parameter to the understanding of space heating is the temperature within the building. Indoor temperatures are determined by the occupants and the building. Indoor temperatures provide a measure of the ‘service’ the occupants get from the space heating within the building. The 1971/72 Insulation-Temperature study[6] showed that indoor temperatures in New Zealand houses are low. Increased expectations for higher indoor temperatures may result in increased demand for space heating unless the delivery of space heating is improved. Data logger technology has advanced in recent years to allow for the measurement of indoor temperatures with a short time interval (ten or fifteen minutes). These detailed temperature time-series provide information on the effectiveness of the space-heating systems as well as the dependence of the indoor temperatures on external conditions[19]. Sensor placement is a critical issue for the measurement of indoor temperatures and this is currently under investigation in the HEEP project.

4. Conversion to Energy

4.1 Electricity

Calculations are required on the output of the data loggers to convert the output of each sensor into units of energy. Each pulse output of the Siemens meter corresponds to a 0.001 kWh and consequently the output for electricity requires no further processing.

4.2 Solid Fuel

The measurements for solid fuel are indirectly related to the energy content of the fuel going into the burner. The surface temperatures provide information on the conductive and radiative heat release of the solid fuel appliance to the room. The notebook record is used in conjunction with the temperature measurements and the estimate for the efficiency of the appliance to provide information on the input energy of the solid fuel burner.

4.3 Gas

The measurement provided by the gas sensor is the volume of gas passed through the gas meter. The heat content Q of the gas passed through the meter is related to the volume at standard conditions V_0 by the following equation

$$Q = V_0 \cdot H \qquad (1)$$

where H is the volumetric calorific value of the gas at standard conditions. Standard conditions are at a temperature of T_0 = 288.15 K = 15 °C and a pressure of P_0 = 101.325 kPa.

The volume displayed on the gas meter is not the volume at standard conditions but is the volume at actual conditions. Considering a fixed quantity of gas and by using the ideal gas laws the pressure, temperature, and volume of the gas at actual conditions can be related to the pressure, temperature and volume at standard conditions by

$$\frac{P \cdot V}{T} = \frac{P_0 \cdot V_0}{T_0} \qquad (2)$$

When equation 2 is combined with equation 1 the heat content of the gas can be written as

$$Q = \frac{P \cdot T_0 \cdot V}{P_0 \cdot T} H \qquad (3)$$

In addition to the measurement of the volume of gas at actual conditions information is also required on the pressure and temperature of the gas at actual conditions as well as the calorific value of the gas at standard conditions. It is possible to use expensive flow meters with correction devices to account for the gas not being at standard conditions however for the present application requiring the installation of a large number of meters, the additional cost is prohibitive. Instantaneous correction is therefore not possible and the parameters are averaged before they are combined together. This 'average' correction will be important depending on the variability of the parameter. The time over which this average correction is made is limited by the data sources available. Climate information is commonly available with hourly intervals.

The gas measurement standard[20] NZS5259:1997 is concerned with the custodial transfer of gas and makes corrections to the volume at actual conditions by introducing correction factors for the gas temperature F_T the regulator setting F_P and the height of the meter F_A . These correction factors are separately calculated allowing equation 3 to be written in the form (compressibility of the gas is not considered)

$$Q = F_T \cdot F_P \cdot F_A \cdot V \cdot H \qquad (4)$$

4.3.1 Gas Calorific Value

Measurement of the calorific value of reticulated natural gas at standard conditions is conducted on a daily basis by the gas supplier, Natural Gas Corporation. These calorific values are determined some distance from the house being measured and consequently there will be a time delay before the gas that has been measured actually passes through the gas meter. Calorific values were supplied by Transalta for the period 31st March 1998 to 10th August 1998. The calorific value had a mean of 40.8 MJ/m^3 and a sample standard deviation of 0.3 MJ/m^3 (0.8% of the mean) over this period. In the absence of more detailed data the daily calorific values will be used to approximate the instantaneous calorific value of the gas. The standard uncertainty in the calorific value measurement will be approximated by the standard deviation of 0.8%.

LPG is predominantly sold as mixture of 40% propane and 60% butane[21]. When gas is drawn-off from the cylinder, propane is preferentially vaporised. Initially the gas content by Raoult's law[22] is 70% propane and 30% butane. As the cylinder is emptied the composition of the gas contains an increasing proportion of butane. The calorific value of LPG is therefore dependent on how much gas has been drawn off from the cylinder. Without knowing how much gas has been drawn off from the cylinder a gross calorific value is chosen between the value for a 70/30 propane-butane mix (108 MJ/m^3) and the value for butane (125 MJ/m^3). A value of 118 MJ/m^3 with a standard uncertainty of 5 MJ/m^3 (5%) will therefore be used for the gross calorific value of LPG.

4.3.2 Gas Temperature

The temperature of the gas is inferred from the medium in which the gas piping leading to the meter is embedded. For reticulated natural gas, this usually corresponds to ground temperature however when the pipework is exposed to the air for some distance, the air temperature will have an effect on the gas temperature. The temperature of LPG is close to room temperature when portable indoor LPG cylinders are used. As the temperature is inferred on the gas before is passes through the gas regulator when the pressure reduction due to the regulator is large the temperature drop as a consequence of the Joule-Thompson effect may need to be accounted for. Enthalpy of the gas is the same before and after the regulator. For portable LPG cylinders, the absolute pressure on the high side of the regulator is approximately 170 kPa whereas for reticulated natural gas the absolute pressure is approximately 190 kPa.

Hourly ground temperatures are only available for a few sites in New Zealand. The Kerikeri site (NIWA agent no 1056) was identified as such a site. While Kerikeri is some distance from the measurements currently underway in Wellington it is the relationship between variance of the air temperature and the variance of the ground temperature that is of interest. It is assumed that these variances will have a similar pattern in other locations. The ground temperatures analysed were recorded at a 30 cm depth. This depth was selected as being representative of the depth of residential gas pipework. The 1998 hourly records of ground temperatures at a 30 cm depth and mean air temperatures were extracted from the NIWA Climate database[23]. Daily information was taken as the readings made at a particular time of the day, usually 9am.

Temperature can be represented as a time-series with proportions of the variation attributable to seasonal effects and to daily effects. The hourly data will be taken as the best approximation to the instantaneous value of the parameter in question. The variation in the hourly data will not take into account the seasonal and daily effects and will indicate the uncertainty arising by replacing the temperature by the annual mean of the temperature. For the ground temperature the standard deviation of the total hourly data was 3.6 K (1.2% of the mean) whereas air temperature was slightly more varied with a standard deviation of 4.5 K (1.5% of the mean) in the total data. Seasonal effects can be taken into account by breaking down the time series into the sum of a daily value (taken as the value at 9am) and the difference between the current hours' reading and the daily value (the daily adjustment). The improvement between the total variation and the variation of the daily adjustments indicates the importance of the seasonal effects in the temperature. For the air temperature the standard deviation of the daily adjustment was 3.2 K (1.1% of the mean) whereas for the ground temperature the standard deviation showed a considerable improvement when seasonal effects are taken into account with a value of 0.2 K (0.1% of the mean). The standard deviations for the ground and air temperatures are summarised in TABLE 1. The ground acts as a moderator of the temperature and hourly variation is more controlled. The variation in the ground temperatures when seasonal effects are taken into account are more precise.

Variation Within	**Air Temperature**	**Ground Temperature**
Hourly temperature data	1.5%	1.2%
Differences between current hour temperature and 9am temperature for the same day.	1.1%	0.1%

TABLE 1 Variation amongst temperature data as a percentage of the corresponding mean

In keeping with Equation 4, the temperature factor to apply to an individual measurement is

$$F_T = \frac{T_0}{T} \qquad (5)$$

where T_0 = 288.15 K and T is the absolute temperature measured in Kelvin. For HEEP, reticulated natural gas will be calculated from the daily ground temperatures with the uncertainty in the temperature factor taken as 1%. LPG will be taken as following room temperature and the daily room temperature will be assumed to give rise to an uncertainty in the temperature factor of 2%.

4.3.3 Gas Pressure

Information about the pressure of the gas is gained by the use of a gas pressure regulator which sets the gas pressure to a specific level before it enters the gas meter. Gas pressure regulators are gauge devices in that they set the pressure relative to atmospheric pressure. The pressure of the gas can then be written as

$$P = P_g + P_m \tag{6}$$

where P_g is the gauge pressure set by the pressure regulator before the meter and P_m is the atmospheric pressure at the meter. The pressure of the gas as it passes through the regulator generally drops with increased flow. The size of this drop is known as 'droop' and is of the order of 20% over the working pressure range[24]. For reticulated natural gas the highest expected regulator setting is 3.0 kPa producing a standard uncertainty in the gauge pressure of 0.3 kPa. For LPG, the adjustable regulator is set to 7.0 kPa producing a standard uncertainty in the gauge pressure of 0.8 kPa. Imprecision in the setting of the regulator is allowed for by taken the standard uncertainty of the gauge pressure as 1.0 kPa. Expressed in terms of factors the correction for gauge pressure is given as

$$F_P = \frac{P_g + P_0}{P_0} \tag{7}$$

The atmospheric pressure at the meter P_m can be broken down into two components; one is the systematic decrease of pressure with height and the other is the fluctuation of atmospheric pressure at that particular height.

Considering first the variation in the pressure due to the fluctuation of atmospheric pressure at mean sea-level P_{msl} about pressure at standard conditions P_0 . Daily pressure information is available for a number of meteorological sites in New Zealand. This daily pressure data consists of the pressure recorded at a particular time of the day. Hourly pressure data is available for a smaller selection of sites. Hourly reduced mean sea-level pressure data from the NIWA Climate database[23] was examined for 1998 from Wellington Airport (NIWA agent no 3445*)*. The hourly pressure data had a sample standard deviation of 0.9 kPa. Using the standard pressure (101.325 kPa) in-place of the hourly data will consequently result in an uncertainty of approximately 0.9 kPa. If greater accuracy is required, the 9am measurement of pressure could be used in place of the standard pressure. The sample standard deviation of the hourly differences from the 9am measurement of pressure was 0.3 kPa. Using daily data in place of standard pressure will improve the approximately standard uncertainty of the atmospheric pressure at mean sea level from 0.9 kPa to 0.3 kPa.

Considering now the systematic variation, the hydrostatic equation gives a differential equation for the atmospheric pressure P_m as a function of height[25].

$$\frac{dP_m}{dz} = -\rho \cdot g \tag{8}$$

where ρ is the density of the air and g is the acceleration due to gravity (taken as 9.8 ms^{-2}) and the air is assumed to be homogeneous. Taking the air as an ideal gas this equation can be solved for the pressure P_m at a height z above mean sea-level

$$P_m = P_{msl} \exp\left(-\frac{gMz}{RT_v} \right) \tag{9}$$

where P_{msl} is the atmospheric pressure at mean sea-level, M is the molecular weight of air (0.028964 $kg\cdot mol^{-1}$), R is the universal gas constant (8.314 $J\cdot mol^{-1}\cdot °C^{-1}$) and T_v is the mean virtual temperature of the air layer between mean sea-level and height z. The height of the meter above sea level is determined from topological maps of the area. These maps provide 20 m spacings of the contours, consequently the standard uncertainty in the height is approximately 6 m. To provide a level of consistency with NZS5259:1996 in calculating equation 9 an average value is taken for T_v so that

$$k_2 = \frac{RT_v}{gM} = 8500 \text{ m} \tag{10}$$

The uncertainty for T_v will be no greater than 1.5% considering the hourly variation in air temperature from TABLE 1. The altitude factor for equation 4, will then be

$$F_A = \frac{P_g + P_0 \exp\left(-z / k_2\right)}{P_g + P_0} \tag{11}$$

NZS5259:1996 differs slightly from this equation in that a linear approximation of the exponential function is used.

The standard uncertainty[16] in the atmospheric pressure at the meter $u(P_m)$ is taken as follows

$$u^2(P_m) = \left(\frac{\partial P_m}{\partial P_{msl}}\right)^2 u^2(P_{msl}) + \left(\frac{\partial P_m}{\partial z}\right)^2 u^2(z) + \left(\frac{\partial P_m}{\partial T_v}\right)^2 u^2(T_v) \tag{12}$$

On substituting and approximating by taking $\exp\left(\frac{-2gMz}{RT_v}\right) = 1$

$$u^2(P_m) = u^2(P_{msl}) + \alpha\left(\frac{1}{T_v^2}\right)u^2(z) + \alpha\left(\frac{z^2}{T_v^4}\right)u^2(T_v) \tag{13}$$

where $\alpha = \left(\frac{-gMP_{msl}}{R}\right)^2 = 1.2 \times 10^7 \text{ N}^2\text{m}^{-6}\text{K}^{-2}$ when P_{msl} = 101.325 kPa.

Large values for equation 13 are considered by taking T_v = 273.15 K = 0 °C and z = 500 m. Using the standard pressure for P_{msl} so that $u(P_{msl})$ = 0.9 kPa results in a value for the uncertainty of the atmospheric pressure at the meter $u(P_m)$ of 0.9 kPa. Over 95% of the variance in the atmospheric pressure at the meter P_m is due to the variation in atmospheric pressure P_{msl}. Using daily values for the atmospheric pressure P_{msl} reduces the uncertainty in the atmospheric pressure $u(P_{msl})$ to 0.3 kPa however over three quarters of the variance in the atmospheric pressure at the meter P_m is still due the atmospheric pressure P_{msl}. The overall uncertainty in the atmospheric pressure at the meter when daily values are used becomes $u(P_m)$ = 0.3 kPa. For the HEEP calculations standard atmospheric pressure will be used for P_{msl}. Both the variation due to the approximation of the height of the meter and the variation due to approximation of the mean temperature of the air between sea level and the height of the meter are small.

4.3.4 Gas Energy Content

The calculation of the energy content of the gas is determined by multiplying the measured volume by the correction factors according to equation 4. Applying an uncertainty analysis to this equation the standard uncertainty[16] for the energy content of the gas is given by

$$\left(\frac{u(Q)}{Q}\right)^2 = \left(\frac{u(F_T)}{F_T}\right)^2 + \left(\frac{u(F_P)}{F_P}\right)^2 + \left(\frac{u(F_A)}{F_A}\right)^2 + \left(\frac{u(V)}{V}\right)^2 + \left(\frac{u(H)}{H}\right)^2 \tag{15}$$

From the estimates of the uncertainties from sections 4.3.1 to 4.3.3, the overall uncertainty in the energy content of the gas for Reticulated Natural Gas and for LPG can be summarised as follows

$(2.0\%)^2 = (1.0\%)^2 + (0.3\%)^2 + (0.9\%)^2 + (0.9\%)^2 + (0.8\%)^2$ Natural Gas

$(6.0\%)^2 = (2.0\%)^2 + (1.0\%)^2 + (0.9\%)^2 + (0.9\%)^2 + (5.0\%)^2$ for LPG

The uncertainty in the measurement of the energy content of reticulated natural gas is seen to be fairly evenly proportioned amongst the correction factors for temperature and altitude as well as the measurement of gas volume and gas calorific value. The effect of the gauge pressure correction factor for reticulated natural gas is seen to be small. If daily atmospheric pressure is used for P_{msl} in place of the standard pressure then the value of the uncertainty in the energy content is unchanged (at one significant figure) at 2%.

The uncertainties in the LPG measurement are higher and more varied than the uncertainties for reticulated natural gas. Over 70% of the variance in the energy content of the gas is attributable to the high uncertainty of the calorific value of the LPG. One method to reduce this uncertainty is to determine the propane/butane composition of the LPG during the measurement and apply the calorific values of butane and propane accordingly.

5. Conclusions

Data is analysed on a variety of timebases. To permit maximum usefulness of the data, the logging interval should be chosen as short as possible. The time interval for the loggers used to record whole building energy use for HEEP are set to either one or two minute logging. These one and two minute profiles are aggregated to ten minutes for input in the HEEP database.

The methods used in HEEP to estimate electricity usage within a house have an uncertainty of 2%. Gas energy use is calculated by using meters to record the volumetric gas flow and then applying factors to correct for the actual conditions encountered by the meter. The uncertainty in the energy content of reticulated natural gas (2%) is better than the uncertainty in the energy content of LPG (6%). This is due to better understanding of the physical properties of the gas and hence the correction factors for reticulated natural gas than is available for LPG. While the uncertainties in the correction factors for reticulated natural gas are fairly even the uncertainty due to the calorific value of the LPG is a large factor in the uncertainty of the energy content of LPG.

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