5B.6 HUMAN BIOMETEOROLOGICAL DIMENSIONS OF RESIDENTIAL ENERGY CONSUMPTION

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1. INTRODUCTION

Australian electricity suppliers Pacific Power and Sydney Electricity carried out a Residential Energy Study (RES) in New South Wales (NSW) during 1993-1994 (Camilleri, Isaacs et al. 2000). The study involved directly metering the energy end-use of household appliances in a sample of houses across NSW. The present paper specifically examines weather sensitivity in electricity consumed by room air-conditioners monitored in that study within the Sydney metropolitan region. Statistical relationships observed between outdoor weather and individual appliance energy consumption for an 18-month sample period are used to quantitatively define the weather sensitivity of appliance energy consumption.

1.1 Weather Sensitivity of Electricity Consumption

In most electricity systems the residential sector is one of the main contributors to system peaks (Bartels and Fiebig 2000). Usage patterns of many household appliances such as heating and air-conditioning (HVAC) are expected *a priori* to be affected by outdoor weather variations, but of course energy consumption will also depend on building envelope characteristics and occupant behavior. The latter is subject to myriad influences, including householders' subjective comfort preferences (Busch 1992; Wong, Feriadi et al. 2002), their socio-demographic characteristics (RECS 1997; Camilleri, Isaacs et al. 2000), subtle cognitive factors (Lutzenhiser 1992), and even cultural dimensions (Busch 1992; Prins 1992; Brager and de Dear 2002).

The present study is the first of its kind in Australia where directly monitored energy consumption is analysed alongside concurrent weather observations. Awareness of the weather sensitivity in energy end-use can provide more information on actual in-use energy consumption for comparison with laboratory measurements on domestic appliances. This knowledge may also provide practical benefits in relation to the implementation of testing procedures for Australia's Minimum Energy Performance Standards (MEPS) and energy efficiency programs such as star rating energy labels.

1.2 Aims of the Project

1) Quantify the dependence of residential electrical appliance energy consumption on the outdoor atmospheric environment in Sydney.
2) Define the most appropriate outdoor thermal climate index affecting energy consumption for residential space heating and cooling.
3) Empirically define appliance usage threshold temperatures and whether they match assumed heating and cooling degree-day base temperatures.

2. METHODS

The greater metropolitan Sydney region was split into two zones, one coastal and another inland, each found to be climatically homogeneous (BoM 1991), and well represented by one of two automatic weather stations operated by the Australian Bureau of Meteorology (Sydney and Bankstown Airports). Half-hourly outdoor temperature data from two automatic weather stations within the Greater Sydney metropolitan region were used to calculate degree-days for each of the 568 days of the study period. A degree-day base temperature of 18°C was used in the following project, as in some earlier Australian research (Badescu and Zamfir 1999), although there is no universal agreement on this. A common approach in the energy sector has been to use 18ºC for heating degree-days and 24ºC for cooling degree-days (Harrington 2001). The assumption behind this practice is that there is negligible energy consumed for domestic heating or cooling purposes between mean daily temperatures of 18°C and 24°C. An empirical resolution of the question would be to observe the mean daily temperature associated with minimum heating and/or cooling energy consumption, but to-date there has been no such analysis in Australia. In this study degree-days were calculated from "degree half-hours" in order to match the temporal resolution of the residential energy study's plug-load data.

Since the same base temperature of 18ºC is used in summer and winter throughout this report, a negative degree-day in our analyses denotes a heating degree-day and a positive degree-day, a cooling degree-day. This sign convention centered on 18ºC has the advantage of allowing heating and cooling season results to be plotted on the same graph. Degree-days and degree half-hours were also calculated using composite thermal comfort indices, namely Standard Effective Temperature (*SET**) and Effective Temperature (*ET**). *SET** and *ET** are indices used widely in the heating and air-conditioning industry to combine the effects of temperature, thermal radiation, humidity, wind speed, clothing insulation and metabolic rate on human thermal comfort (Gagge, Fobelets et al. 1986).

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3. RESULTS

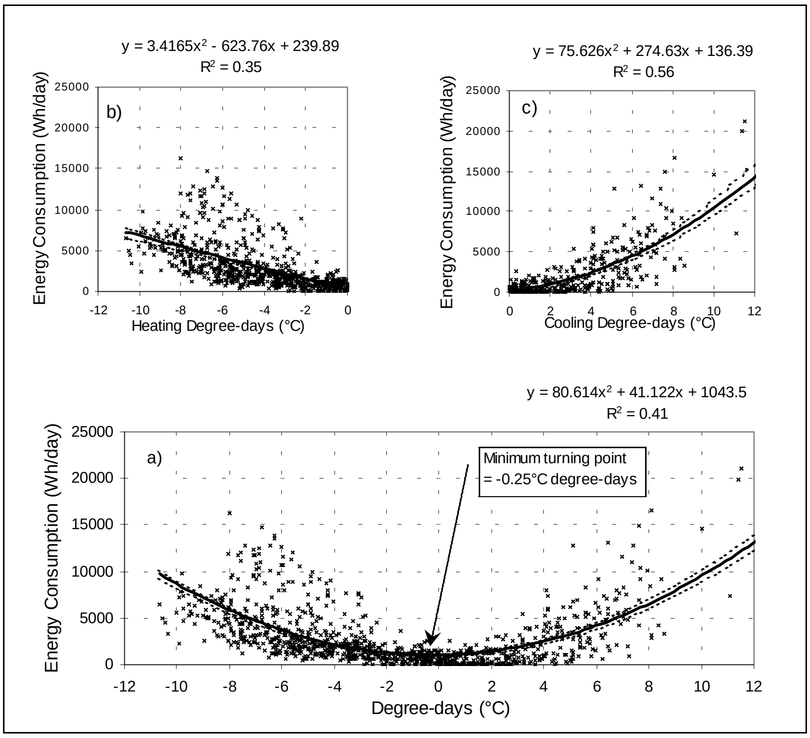

Figure 1 The relationship between air-conditioner average daily energy consumption in Watt-hours per day on the y-axis and degree-days on the x-axis for a) the entire year, b) the heating season and c) the cooling season (empirically defined by the average daily temperature in relation to 18°C). Regression models (solid curves) and 95% confidence intervals (dashed curves) were fitted with 2nd-order polynomials. Energy consumption was averaged over 47 households in the cooling season and 41 in the heating season.

Daily average energy consumption was calculated across all houses within each of the two Sydney climatic zones (coastal and inland), for each of the 48 half-hourly time steps. Sample-wide averages (across all households) for energy consumption (Wh/day) were modelled in relation to degree-days and thermal comfort indices *SET** degree-days and *ET** degree-days. Figure 1 presents the relationship between degree-days and energy consumption over the entire study period, split by season. The relationship is stronger in the cooling season (Figure 1c) when 56% of the variance in day-to-day energy consumption was explained by degree-days, compared to only 35% in the heating season (Figure 1b). The amount of day-to-day variance in air-conditioner energy consumption explained by *SET** degree-days was marginally greater than with either simple air temperature or *ET** degree-days Forty-five percent of the variance in air-conditioner energy consumption over both seasons was explained by *SET** degree-days, compared to only 41% by air temperature degree-days and 39% by *ET** degree-days.

The regression analysis of all-year energy consumption in Figure 1a produced a quadratic equation with a turning point at -0.2ºC degree-days (the point at which the derivative of the function is zero). This point shows the degree-day value when neither heating nor cooling is required, or when they are least in demand.

Probit analysis is a statistical technique that models the percentage of a sample responding to various levels of exposure to an environmental agent (SAS 1999). In the context of the present project the technique was used to fit sigmoidal response functions between the daily temperature or degree-day (stimulus) and the percentage of sample households with their air-conditioners (either in heating or cooling mode) switched on at least once during the day in question. During the heating season probit regression between degree-days and the probability of appliances being switched on (Figure 2a) produced a small chi-square test statistic for goodness of fit and therefore a large P-value (χ^2=15.5,df=20,P=0.8), indicating a good fit by the probit model*. The probit model's 50% threshold temperature was -7.2°C degree-days (ie a mean daily temperature of 10.8º C), with narrow fiducial limits from -7.6ºC to -6.8ºC degree-days (fiducial limits are to probit models what confidence limits are to regular regression models). This 50% threshold average daily temperature (or degree-day) is the point at which 50%

* In the context of this particular statistical method, failing the χ 2 goodness of fit test at the 0.05 level indicates that the data were well approximated by the probit model.

of occupants had their appliance switched on at some stage during the day and the other 50% had it switched off all day. This is also the point at which the greatest number of households changed their decision from "off" to "on". Figure 2b shows the results of cooling season analysis in which the probit model produced a large chi-square test statistic and a low P-value (χ^2=34.2,df=20,P=0), indicating there was a relatively weak match between the probit model and the data, but this was compensated for by widening the fiducial limits. The 50% threshold temperature for cooling season analysis was 5.5ºC degree-days with 95% fiducial limits of 5.1ºC and 6.0ºC degree-days. It should be noted that the implementation of the probit technique that we used SAS (SAS 1999) was able to compensate for failed goodness of fit tests by widening the fiducial limits surrounding its estimate of the 50% threshold temperature.

On extending the weather sensitivity analysis by using the *ET** and *SET** thermal comfort indices instead of air temperature during the cooling season, the probit regression model of air-conditioner usage and *SET** degree-days produced the best results in terms of explained variance and maximised goodness of fit test (χ2=7.5,df=16,P=0.9). The 50% threshold temperature came in at 3.3ºC *SET** degree-days with tightly defined 95% fiducial limits at 3.0°C to 3.6°C *SET** degree-days.

Load profiles were calculated for the air-conditioners in the Sydney sample in order to closely examine the diurnal variability of energy consumption. Mean hourly energy consumption and concurrent outdoor air temperature observations were averaged across all households for each hour of the day. Due to the two modes of reverse cycle air-conditioners (heating and cooling), separate load profiles were produced for heating and cooling seasons i.e. averaging across all days in each of the two seasons. Figure 3 shows the diurnal distribution (time uncorrected for daylight savings) of air-conditioner energy consumption and corresponding outdoor air temperature for the heating and cooling seasons (a) and (b) respectively. The salient feature of the seasonal comparison in Figure 3 is the mean daily energy peak in winter is twice that for summer. During the cooling season (Figure 3b) energy consumption begins to rise at 9am, peaking at 4pm and then rapidly decreasing to a minimum at 6am, closely tracking the diurnal outdoor temperature cycle. Assuming the causal link between summer temperature and energy consumption extended to the heating season one might expect the winter diurnal load profile to be a mirror image of the summer's, but that appears in Figure 3a to not be the case. Winter heating energy consumption has two peaks: one at 8am and the other at 9pm. During the heating season the daily minimum temperature occurs between 6-7am, but this coincides with the time of minimum, not maximum heating energy consumption. Heating season load profiles for room heaters produced a similar twin-peak pattern to that of air conditioners during the heating season.

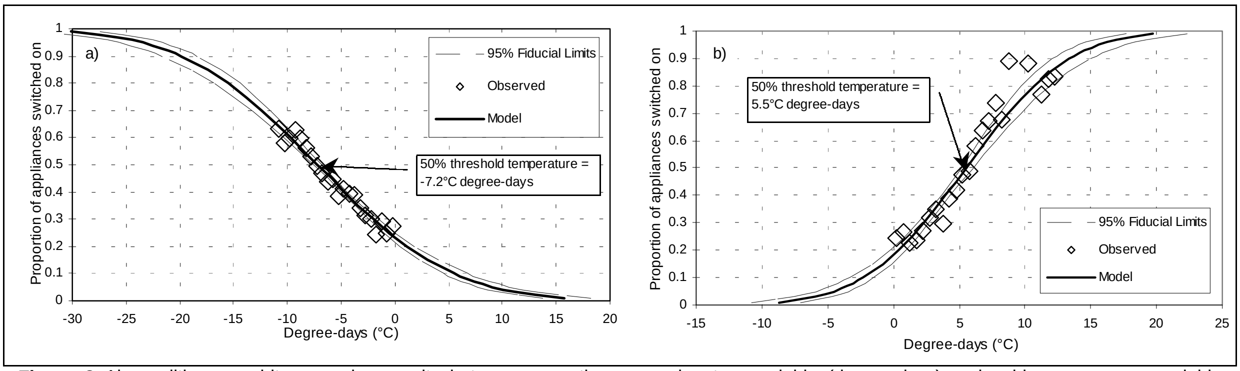

Figure 2 Air-conditioner probit regression results between a continuous explanatory variable (degree-days) and a binary response variable (whether or not the appliance was switched on at any time during the day). Analysis is performed separately for a) heating season, and b) cooling season.

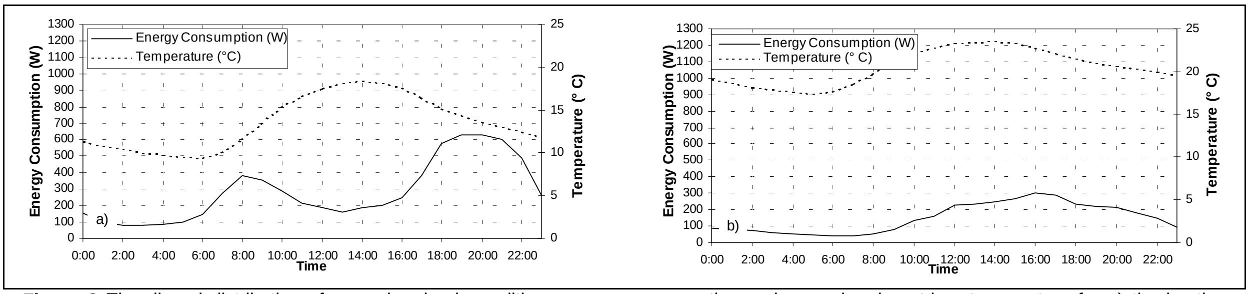

Figure 3 The diurnal distribution of mean hourly air-conditioner energy consumption and mean hourly outdoor temperature for a) the heating season, and b) the cooling season. Energy consumption is averaged across 47 appliances for the cooling season and 41 appliances for the heating season.

4. DISCUSSION

The severity of climate can be characterised concisely in terms of degree-days. The degree-day base temperature is generally regarded as the outdoor temperature at which neither artificial heating nor cooling is required. Heating degree-days, or degree-hours, calculated with respect to a base temperature of 18°C are widely used in Australia (Badescu and Zamfir 1999). For cooling degree-days however, the base temperature is not so unanimously agreed. Often different base temperatures are used for cooling degree-days, depending on the building type and ventilation rate (ASHRAE 1993). Unfortunately the design features and ventilation capabilities were not recorded for the houses in the present study, so a constant cooling degree-day base temperature of 18°C was applied across the entire sample. The results of reverse-cycle air-conditioner energy consumption versus degree-days in Figure 1 indicate the parabolic minimum occurred at -0.2°C degree-days, so a degree-day base temperature of 18°C seems to be confirmed by these data from the Sydney context. The relationships for both seasons demonstrated that, at an average temperature above 18°C in Sydney, householders start using their coolers more intensively, and with an average daily temperature below 18°C, householders start making more use of their air-conditioners in heating mode. The non-zero energy consumption minimum in Figure 1a indicates that some households in our sample were cooling their houses on days cooler than a mean of 17.75° C and heating their houses on days warmer than that base temperature.

The relationship between outdoor weather and air-conditioner energy consumption was stronger in summer than in winter (R^2 =0.56 for summer, compared to 0.35 for winter). Reverse cycle air-conditioner load profiles indicate that peak energy consumption occurs in the late afternoon during summer and in the evening during winter. Outdoor temperature minima occur in the early morning and maxima in the mid afternoon. Consequently, during the heating season at the coldest time of the day, occupants are sleeping and, as a result, energy consumption is minimal. The lack of heating during this coldest time of the day undoubtedly weakened the statistical relationship between daily energy consumption and heating degree-days, reinforcing the importance of time-of-day in the prediction of space heating energy consumption. Further reinforcing this interpretation is the observation that, during the cooling season (summer) when air-conditioner load peaks in the afternoon (coinciding with the warmest time of the day), house occupants were more likely to be awake and therefore more likely to respond to the heat by turning on their air conditioners, thus explaining why the statistical relationship between daily energy consumption and degree-days was stronger in summer than in winter.

One of the key outputs from the probit regression program is a 50% threshold temperature which can be interpreted as the temperature at which the largest proportion of households change their appliance from “off” to “on”. These results, along with load profiles, and the direct relationships produced between energy consumption and outdoor weather may potentially be useful for power utility operations in predicting system spikes and peaks in the Sydney market. Since the residential sector in general and space heating and cooling appliances in particular have a large impact on electricity peak loads (Bartels and Fiebig 2000), the weather sensitivity results reported here, along with appliance penetration rates, are potentially useful in relating system peaks to individual end-uses in the residential sector.

5. CONCLUSIONS

Statistical models were established between outdoor weather and energy consumption for room air-conditioners. The relationship between outdoor weather and individual appliance energy consumption was found to be stronger in the cooling season than the heating season for all appliances, including those not discussed in this paper. The thermal comfort index *SET** was found to be the most useful of predictor of space cooling energy consumption, indicating that outdoor wind speed and relative humidity, as well as air temperature affect occupants’ thermal comfort, which, in turn, determines space cooling demand.

Probit regression was found to be a useful statistical technique in predicting the degree-day values at which households tend to heat and cool. Probit models of space heating and cooling appliance usage patterns can predict the probability of the appliances being switched on under various outdoor weather conditions. These relationships, along with load profiles and the direct relationships between energy consumption and outdoor weather, have the potential to assist in the prediction of system spikes and peaks.

By examining the mean daily temperature associated with minimum heating and cooling energy consumption for Sydney, a degree-day base temperature of 18°C was found to be the appropriate base temperature for the calculation of both heating and cooling degree-days. This report is the first empirical confirmation that 18°C is the most appropriate degree-day base temperature for Sydney, all-year-round.

The quantitative weather sensitivities defined in this study have been applied to long-term climatological observations and greenhouse climate predictions in order to forecast potential impacts of climate change on household appliance energy end-use in the Sydney region (Hart and de Dear 2002).

Suggestions for future research arising from the present project include a more thorough application of the *ET*, SET*,* and other thermal climate indices of thermal climate to modeling outdoor thermal conditions. In particular, instead of assuming mean radiant temperature equal to air temperature (i.e. shade condition), it is feasible to explicitly calculate the impacts of short- and long-wave radiation on the human heat balance and to equate these impacts to the temperature of an isothermal enclosure that would be required to exert the same net radiation impact (Blazejczyk, Nilsson et al. 1993) i.e. mean radiant temperature. This avenue of further research would enable a quantitative assessment the impacts of solar radiation variations on energy end-use.

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