Climate zones for load analysis: a review

BC Hydro Power Smart: Load Analysis
Power Smart and Customer Care
BC Hydro, Burnaby, British Columbia

June 9, 2009

Climate zones for load analysis: a review

Introduction

Electrical utilities know from experience that load demand is weather dependent. Whether or not climate zones are needed for load analysis depends on the physical geography of the territory served by a utility. British Columbia, served by BC Hydro, has three to over a dozen major climate zones depending on the purpose of the zoning.

The purpose of this paper is to review the use of climate zones for load analysis by other electrical utilities. The review includes climate classification for building energy codes because of that field's direct link to energy demand by building occupants.

The reason for this review is to provide a foundation for Hydro's load analysts to evaluate the appropriateness of their current use of zones and weather/climate data. The Hydro load analysis team is interested in adopting innovative, scientifically sound methods for improving the quality of analyses.

The scientific basis for thermal energy demand is discussed in the Appendix.

Climate zones for load analysis at BC Hydro

For substation load forecasts, weather effects are treated as short term factors with ambient temperature regarded as influencing residential demand through space heating and cooling (BC Hydro, 2007). Commercial and industrial demand is regarded as relatively insensitive to weather events. Distribution planning places minor importance on wind and sunshine hours as weather variables. Sunshine hours are, however, related to solar heating gain and indoor lighting use.

Four climate zones with representative weather stations (Table 1) are used for load analysis (Yu, 2007). These zones correspond to BC Hydro's billing regions. A typical meteorological year (TMY) was constructed using the rank and median method with hourly weather data from Environment Canada. Weather variables included wind speed, dry bulb temperature, total cloud opacity, and wind direction. Yu stated, however, "…weather related demand for electricity is driven mostly by temperature". Rank and median was applied only to temperature.

Table 1: Climate zones for load analysis at BC Hydro (from information in Yu, 2007)

Climate zone	**Representative weather station**
Metro Region	Vancouver International Airport
Vancouver Island	Victoria International Airport
Northern Region	Prince George Airport
Interior Region	Kelowna / Kamloops Airports

Building types are the starting point for analysing weather response as opposed to evaluating only temperature response (Nelson, 2003b). Figure 1 illustrates this paradigm.

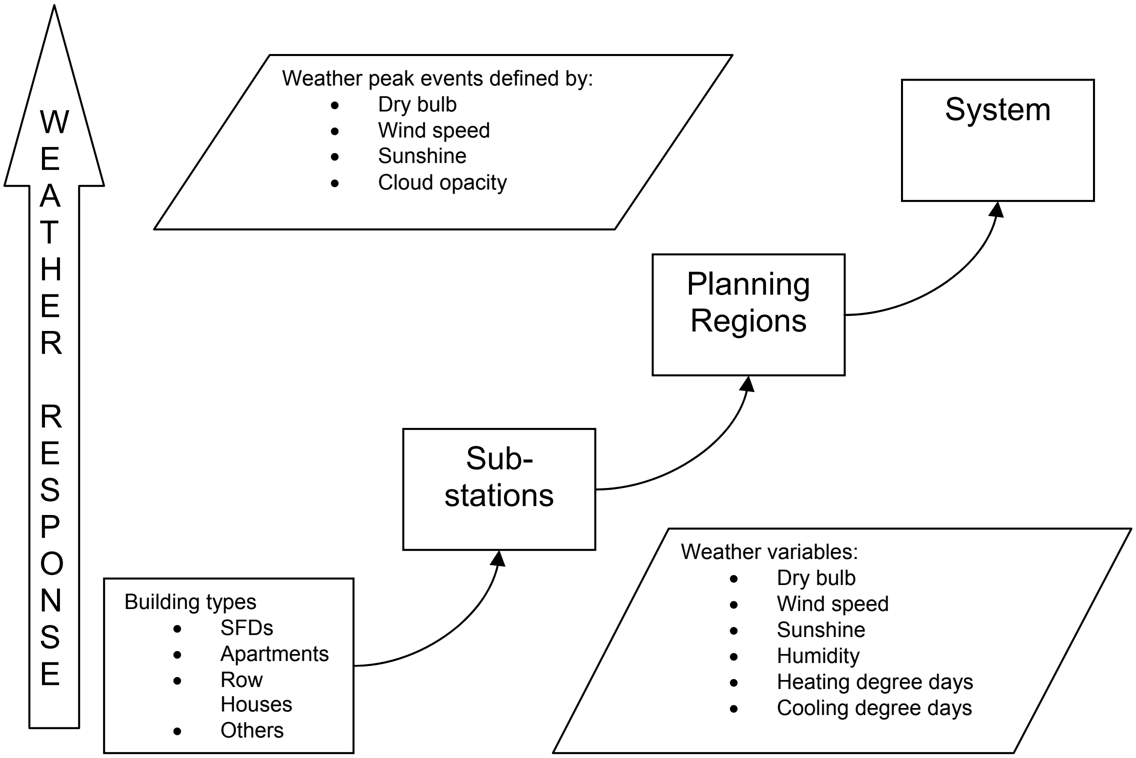

Figure 1: A model for analysing weather response creating demand in an electrical utility distribution system—building type starting point (based on Nelson, 2003b; 2004). SFD = Single family dwelling

At BC Hydro, one of the uses for load analysis is to make utility peak load forecasts. The goal is to plan, build, and service customers during periods of highest demand (Nelson, 2003a). A simplified view of highest demand at Hydro is given in Table 2.

Table 2: Reasons for demand from BC Hydro's account types (from information in Nelson, 2003a, 2004)

Account type	**Basis for highest demand**
Residential	Electric space heaters, water heaters, lighting
Commercial	Lighting
Industrial	High operating level

BC Hydro segments residential data by region because the data is weather sensitive. In 2003, the Metro Region, with its representative weather station at Vancouver International Airport, accounted for 45% of the system load (Nelson, 2003a). Although hourly data is used most often, Hydro's load analysts recognize that equipment planning needs data from shorter periods than hourly (Nelson, 2004). Lags are important, with some being as long as several hours. Residential single family dwellings with electric space heat drive seasonal system peaks. These homes also usually have electric water heaters (Table 2). Seasonal lights contribute to a December peak. Peaks are non-coincident amongst buildings and substations and are consequently not possible to add to each other.

Recent research at Hydro used cluster analysis to generate climate zones (Albrechtsen, 2009). Clustering used four years of hourly dry bulb temperature data from 47 weather stations to create ten weather regions.

Climate zones for electrical load or building energy analysis by other researchers

Experiences of other researchers in the field of zoning for electrical load analyses are summarized in this section. Williamson (2003) observed that segmentation (zoning) bases should be objective, easy to determine, stable over time, and group customers with similar loads together (stratification by climate zone). Furthermore, segmentation by geography should capture variations in load shapes, "…caused by weather differences in areas with diverse weather patterns." The number of segments is constrained by cost versus benefit considerations.

Zoning for load analysis

California

A California study of how residential demand response changes with temperature divided the state into four climate zones and assigned population weights to each zone (Herter and others, 2005). The zones are shown in Table 3.

Table 3: California climate zones for load analysis (from information in Herter and others, 2005)

Climate zone	**Representative cities**	**Statewide population weight**
Coast	Arcata, San Francisco, Salinas, San Luis Obispo	12%
Foothills	Santa Rosa, San Jose, Oxnard, Long Beach, western San Diego	47%
Valley	Chico, Stockton, Santa Clarita, Riverside, eastern San Diego	29%
Desert	Redding, Fresno, Bakersfield, Palm Springs	10%

Switzerland

An artificial neural network for short term electrical load forecasting was set up using Swiss power system subareas corresponding to five geographical regions (Piras and others, 1996).

USA

Lawrence Berkley National Laboratory researchers divided the continental USA into 42 climate zones based on representative city HDD/CDD ratios, where HDD are heating degree days and CDD are cooling degree days, both relative to 65°F (Figure 2; Osborn and others, 1999). The climate zoning was done for a study of electrical demand from electrical appliances including space heaters, water heaters, and lighting. Two interesting findings of relevance to Hydro load analysts were: (1) warmer southern regions experience higher water usage (with implications for water heating) [this might be related to the use of evaporative coolers (swamp coolers), according to Dennis Nelson, personal communication] and (2) households in cooler, northern regions heat their water to a higher average temperature [Inlet water is colder; when mixing water to get comfortable temperature, more hot water has to be used (Dennis Nelson, personal communication)].

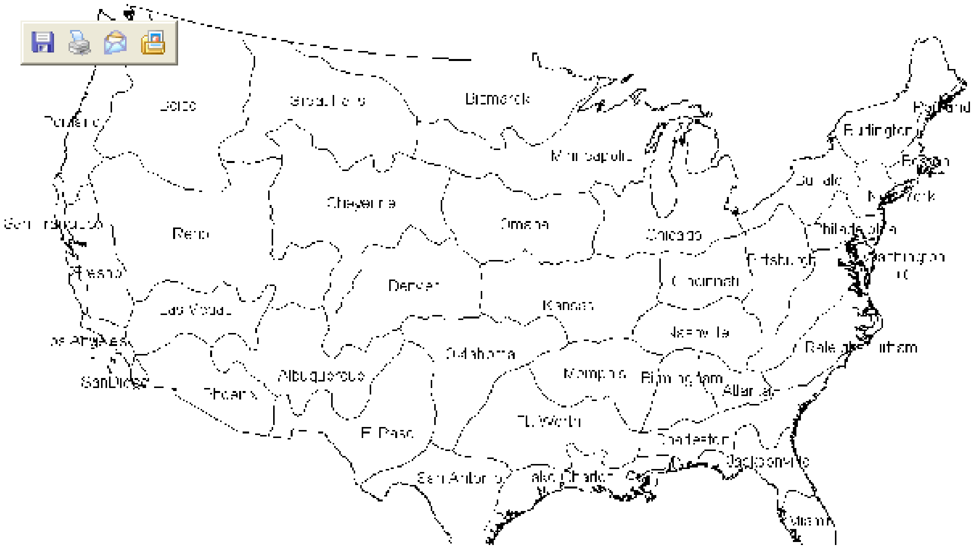

Figure 2: Continental USA divided into 42 climate zones based on representative city HDD/CDD ratio (from Osborn and others, 1999)

Zoning for building energy codes

British Columbia

The British Columbia Building Code (2003) considers the following weather variables: elevations, wind pressure, design temperature (2.5% and 1% for January; 2.5% for July dry bulb and coincident wet bulb), heating degree-days (HDD, 18°C), one day and 15-minute rainfalls, annual total precipitation, ground snow load (kPa), hourly wind pressures (1/10 kPa, 1/30 kPa, 1/100 kPa). Adjustments were made for the influence of elevation and known topographical effects. The Code noted also the following information:

- Wind and solar radiation affect the inside temperature of buildings;
- No adjustments were made for urban heat islands which may be 1–2°C milder than rural or airport sites;
- Heating systems are designed for the 2.5% January design temperature;
- “The rate of consumption of fuel or energy required to keep the interior of a small building at 21 °C when the outside air temperature is below 18 °C is roughly proportional to the difference between 18 °C and the outside temperature”;
- Energy required is proportional to duration of cold spell;
- HDD accuracy is ± 100 HDD;
- Larger cities have HDD values 200 to 400 lower than the surrounding rural area;
- Annual precipitation values are an indicator of climate wetness; and
- Smooth normalized snow load values are ± 20%.

Design data is tabulated for 91 selected locations in BC.

Canada

Climate zones for Energy Star® products comprise four zones based on HDD (18°C, 30 year database; Natural Resources Canada, 2009). The zones are described in Table 4 and shown in Figure 3. Zones A, B, and C are found within BC. There are 48 locations listed in British Columbia (Table 5). Port Hardy was upgraded from zone B to A so that SW BC was kept as a contiguous zone.

Table 4: Climate zones for Energy Star® products (Natural Resources Canada, 2009)

Climate zone	**HDD lower bound**	**HDD upper bound**
A (warmest)	0	3500
B	3501	5500
C	5501	8000
D (coldest)	8000	-

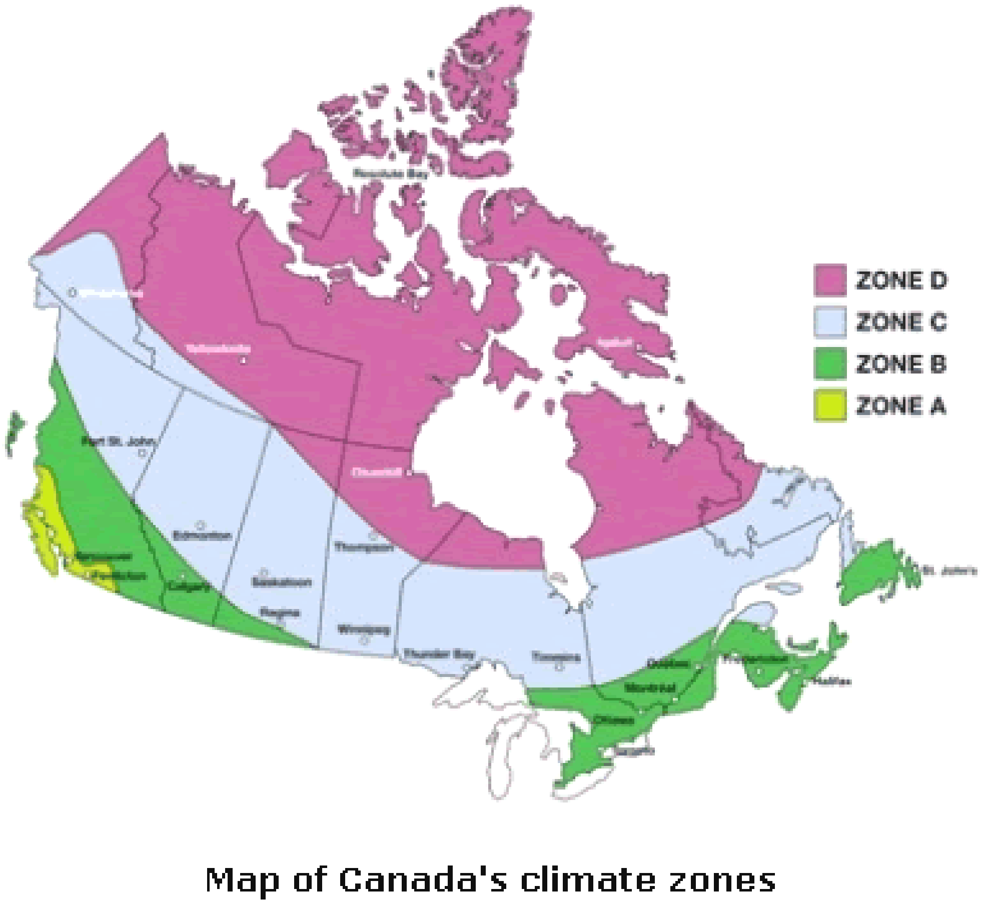

Figure 3: Map of Canada's climate zones based on HDD (18°C) used by Natural Resources Canada in the Energy Star® program. Three of the four zones are in BC. Illustration is from Natural Resources Canada (2009)

Table 5: HDD for 48 locations in BC for Energy Star® reference (Natural Resources Canada, 2009)

Location	Heating Degree Day	Zone
Abbotsford	2981	A
Alert Bay	3459	A
Atlin	6343	C
Bella Coola	3689	B
Castlegar	3678	B
Chilliwack	2833	A
Comox	3083	A
Cranbrook	4576	B
Dawson Creek	5981	C
Dease Lake	6845	C
Estevan Point	3150	A
Fort Nelson	6836	C
Fort St. John	5847	C
Golden	4886	B
Grand Forks	3925	A
Hope	3057	A
Kamloops	3571	B
Kelowna	3869	B
Lillooet	3493	A
Lytton	3309	A
Mackenzie	5714	C
McBride	4971	B
Merritt	3994	B
Merry Island	2726	A
Nanaimo	3056	A
Osoyoos	3210	A
Penticton	3431	A
Port Alberni	3173	A
Port Hardy	3552	A*
Powell River	3210	A
Prince George	5132	B
Prince Rupert	3967	B
Princeton	4364	B
Quesnel	4742	B
Revelstoke	4148	B
Salmon Arm	4044	B
Sandspit	3531	B
Smithers	5135	B
Squamish	3366	A
Stewart	4389	B
Summerland	3525	B
Terrace	4307	B
Tofino	3236	A
Vancouver	2927	A
Vernon	3820	B
Victoria	3041	A
Whistler	4287	B
Williams Lake	5073	B

*This location has been placed in Zone A so that southwestern British Columbia can be one continuous zone.

An annual driving-rain index map of Canada, with three zones or exposure grading (sheltered, moderate, and severe) was discussed by Cornick and Rousseau (2003) as part of a document on severity of climate loads for moisture-related design of walls. Their paper contained information of value to load analysts, namely:

- Driving rain index = annual average wind speed × average annual rainfall;
- Drying potential due to atmospheric moisture is related to cooling potential of evaporative cooling;
- Moisture index = f (Wetting index, (1 – Drying index));
- Outdoor temperature produces a thermal gradient across building walls which affects the air pressure differential across the building envelope. During cold weather, the temperature difference causes cold air infiltration through openings in the lower part of a building. Warm moist air flows out through openings at the top of a building (stack effect);
- Increasing HDD (18°C) is associated with increasing exposure of building walls to cold (duration and/or magnitude); and
- Wind affects the temperature of wall elements. An air pressure differential is created. Outdoor air may enter the wall assembly. This affects temperature distribution across the wall, in turn affecting infiltration/exfiltration patterns.

China

Five cities were selected to represent five climatic zones for building energy research (Table 6). Climatic variables included dry bulb, wet bulb, solar radiation (global, direct, and diffuse), wind speed, and wind direction (Lam and others, 2005).

Table 6: Climate zones for building energy research in China (Lam and others, 2005)

Climatic zone	Representative city
Severe cold	Harbin
Cold	Beijing
Hot summer and cold winter	Shanghai
Mild	Kuming
Hot summer and warm winter	Hong Kong

USA

Pacific Northwest National Laboratory reported on their work developing a new climate classification for building energy codes and standards (Figure 4; Briggs and others, 2002). Their report is a valuable reference, filled with practical information for load analysis teams needing to use climate zones. Essential insights and advice included:

- “Classifications are needed to help generalize knowledge and understanding and for communication with peers.”
- “Any new system for handling climate needs to show substantial improvement over the currently used systems. In addition, any new classification must be at least roughly compatible with current climate-dependent requirements to enable straight-forward translation of current requirements that already enjoy consensus support.”

- “It is not possible to develop a classification for something as complex and multidimensional as climate that will be ideal for all applications and all situations.”

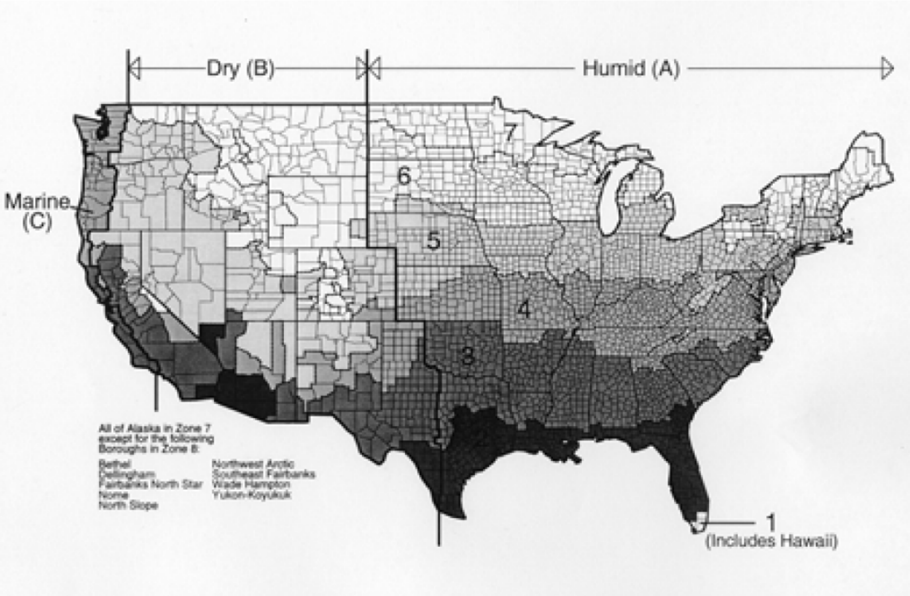

Figure 4: Map of the USA showing new climate zone assignments (Briggs and others, 2002)

Briggs’ team employed hierarchical cluster analysis using climate indices tempered with subjective adjustments to preserve contiguous zones, alignment with pre-existing jurisdictional boundaries, and observing a target of 10 to 20 zones. Briggs emphasized that cluster analysis is a tool for grouping like observations, not an automated process.

A complete set of climate materials includes: maps, zone table, and tabulation of underlying climate criteria.

Elevation impact on climate remains a controversial topic in energy code development.

Climate and load research done without invoking zones

Although the literature is sparse concerning climate zones in load research, there is a substantial body of work about the weather and climate effects on electrical load demand which does not invoke the use of climate zones. This section highlights interesting knowledge accumulated by other researchers some of which may be relevant to tasks facing BC Hydro’s load analysts.

Artificial neural networks

A number of articles discussed the use of artificial neural network (ANN) models for relating demand to weather events. The essential advantage of ANN is that real data can be used to train the model to improve prediction accuracy.

Fuzzy neural networks have been used for load forecasting with improved performance over ANN according to Mepokee and others (2004).

Iran

Hayati and Shirvany (2007) and Yazdi (2009) discussed the use of ANN (multi-layer perceptron type) in Iran for short term load forecasting. Demand could be forecasted on an hourly basis for several days ahead. Weather variables included temperature, humidity, and wind speed. Month and day of week data were also included. Both linear and non-linear relationships can be modeled. Neural networks usually require normalized data for best performance.

Simple regression

Italy

Gas demand, temperature, and seasonality in Italy were studied by Zanotti and others (2003). Although the study was for gas, not electricity, both supply energy for heating so the demand principles are similar. Five aspects of their report worth noting are:

1. Simple regression analyses modeled gas consumption versus temperature, rain, humidity, and pressure;
2. Heating degree-days (HDD) were introduced to "…better capture the non linearity (*sic*) behaviour of gas consumption";
3. Lagged weather variables were implemented;
4. Dummy variables were applied for daily, monthly, and holiday gas consumption patterns; and
5. An error term incorporated an autoregressive structure.

Multiple regression

England and Wales

Parametric multiple regression has an advantage over ANN because the relationship between weather variables and load demand can be explored—this was the opinion of Hor and others (2005). They worked with hourly demand data and supported the widespread view that "Temperature is the main driving factor for load forecasting…" Hor's team noted winter lighting and heating loads coincide with lower temperatures. In summer, air conditioning is used above a critical temperature. When air temperatures are between 14–17°C there is a 'dead zone' within which demand is not very responsive to temperature. Demand saturates at low temperatures. Demand is most sensitive to temperature in the spring and fall. In England and Wales, demand is not as sensitive during the extreme temperatures of summer and winter. Hor and colleagues claimed degree days are a better measure than straight temperature when seeking correlation with demand. Enthalpy latent days can be used to assess cooling load.

Hor and others (2005) did allow that other weather variables should be considered in load analyses. These include: mean monthly wind speed, mean monthly sunshine hours, and monthly rainfall. Hor and associates noticed that wind cools buildings, especially if they are wet. Furthermore: rainfall has a linear relationship to demand, especially for residential load; air-vented dryer load increases during high humidity periods; and an increase in cloud cover increases lighting demand.

Weather ensemble predictions

England and Wales

Taylor and Buizza, 2002) reported on the method of using weather ensemble predictions for modeling relationships between demand and weather. Unspecified non-linear relationships between load and weather variables can be modeled 1–10 days ahead. Prediction uses multiple scenarios for weather variables to produce multiple load scenarios. The average of the load scenarios is more accurate than conventional weather forecasts.

Temperature, wind speed, and cloud cover were used in ensemble predictions by Taylor and Buizza (2003).They stated, "There is no consensus as to the best approach to electricity demand forecasting," and listed time-varying splines, multiple regression models, judgemental forecasts, and artificial neural networks as possible approaches. According to Taylor and Buizza, the National Grid serving England and Wales models demand with three weather variables: effective temperature, cooling power of the wind, and effective illumination.

Effective temperature, TE_t, is a variable that introduces a lag simulating the response of electric heaters to changes in outdoor temperature.

$$TE_t = \tfrac{1}{2}\, TO_t + \tfrac{1}{2}\, TE_{t-1} \qquad (1)$$

where TO_t is the mean of the spot temperature recoded for each of the four previous hours and t is day.

The cooling power of wind, CP_t, variable which is a non-linear function of wind speed and average temperature) simulates load variation caused by drafts. W_t is wind speed.

$$CP_t = \begin{cases} W_t^{1/2}\,(18.3 - TO_t) & \textit{if} \quad TO_t < 18.3\ °C \\ 0 & \textit{if} \quad TO_t \geq 18.3\ °C \end{cases} \qquad (2)$$

The effective illumination variable is a function of visibility, number and type of cloud, and amount and type of precipitation. But, this is a complicated relationship, so Taylor and Buizza found it more practical to use cloud cover, CC_t, to represent effective illumination.

Taylor and Buizza recommended using population concentration to guide assignment of weights to weather variables. As mentioned earlier, this weighting method was used with California's climate zones in the load analysis by Herter and others (2005).

The expression for weather-related demand, WRD, by Taylor and Buizza is a non-linear function of temperature, wind speed, and cloud cover. The non-linearity is a result of the TE_t^2 term in equation (3) and the $W_t^{1/2}$ term in equation (2).

$$WRD = \hat{a}_1\, TE_t + \hat{a}_2\, TE_t^2 + \hat{a}_3\, CP_t + \hat{a}_4\, CC_t \qquad (3)$$

where $\hat{a}_n$ are constants.

Base load (non-weather related demand) can be predicted separately by a univariate auto-regressive moving average (ARMA)-regression model.

Multiple weather scenarios can be input into equation (3) to generate multiple WRD scenarios. The mean of the multiple scenarios provides an accurate demand forecast. Forecasts can be compared using the formula for mean absolute predicted error (MAPE):

$$\text{MAPE} = (1/N) \times \Sigma\ [(P_{\text{actual i}} - P_{\text{predicted i}}) / P_{\text{actual i}}];\ \text{sum from i = 1 to i = N} \qquad (4)$$

where $P_{\text{actual i}}$ = actual load on day i, $P_{\text{predicted i}}$ = forecast value of load on day i, N = total number of data (hours). MAPE is the standard for load forecasts (Yazdi, 2009).

Increasing the value of weather information for load forecasting

China

Load analyses are more representative when geographic distribution is taken into account (Zhang and others, 2006). Heating load is a function of winter air temperatures. Cooling loads are a function of summer temperatures. Zhang and colleagues made the interesting observation that "…degree-hour is a better parameter in predicting cooling load than degree-day because cooling is usually carried out intermittently throughout the day." They also pointed out solar radiation affects both heating and cooling loads.

USA

A workshop in November 2002 in Boulder, Colorado, issued a report (Hackney, 2003) with suggestions of interest to BC Hydro's load analysts. These included:

- "Better demand models will require more accurate forecasts of dry bulb temperature at the micro-spatial scale where the electric demand actually takes place, not at airports…hourly time intervals…higher frequencies…better" (Monforte, 2003);
- "Better load forecasts would result from increased frequency of reporting current data, and improved accuracy of short-range meteorological models: …, local mesoscale effects, cloud cover, and precipitation forecasts (especially in summer convection, which affects peak load forecasts)" (Walshe, 2003);
- "denser networks of weather stations…frequency of reporting (hourly data) needs to be increased" (Wilson, 2003);
- "The weather information needs of the electric power community are highly specialized and not traditionally recognized in weather research. Probabilistic forecasts could help: what is the chance that temperature could exceed a certain threshold? The scientific challenges appear to be in boundary layer meteorology, thermodynamics, new probabilistic and statistics metrics, numerical modeling, and verification with limited data" (Mahoney, 2003); and
- Value of combined physical weather variables such as wind/temperature, humidity/temperature, wind speed/direction, and temperature/duration to give more information than the usual single-variable (often temperature).

Washington State

An integrated engineering-econometric analysis of residential balance point temperatures used data from Puget Sound Energy, Washington State (Dubin, 2008). Dubin, like most load researchers, stated, "Temperature is the most important factor in load forecasting." He observed that the relationship between load and temperature is non-linear. This is attributed to the laws of thermodynamics, limitations of HVAC equipment, and air infiltration. Dubin noted, "…while the relationship between load and temperature has been known to be highly non-linear, applied researchers and utilities continue to adopt simple linear relationships between load and temperature often relying on summary measures such as the heating degree days at an assumed base temperature (typically 65 °F)."

Dubin found that use of HDD65F understated the elasticity of demand between usage and temperature. The balance point temperature = f (thermostat setting, thermal properties of building envelope). For a well insulated house with several occupants and appliances in use, HDD65F would over-estimate the energy needed for heating.

Finally, Dubin noted there is a quadratic relationship between indoor and outdoor temperatures and temperature differential. An estimate of the energy lost per hour due to the temperature differential is given by the quadratic approximation:

$$Q(t_o) = w_0 + w_1 \times (t_i - t_o) + w_2 \times (t_i - t_o)^2 \quad (5)$$

where

t_o = outdoor temperature;
t_i = indoor temperature (thermostat setting);
w_0 = a constant which is negative if there is sensible heat gain from occupants and appliances; and
w_1, and w_2 are, like w_0, constants related to the building's thermal characteristics (air volume, insulation levels, etc.).

When w_0 is negative, there is a balance temperature, t_b (Figure 5). Once temperatures decrease below t_b, heating is required (Figure 5).

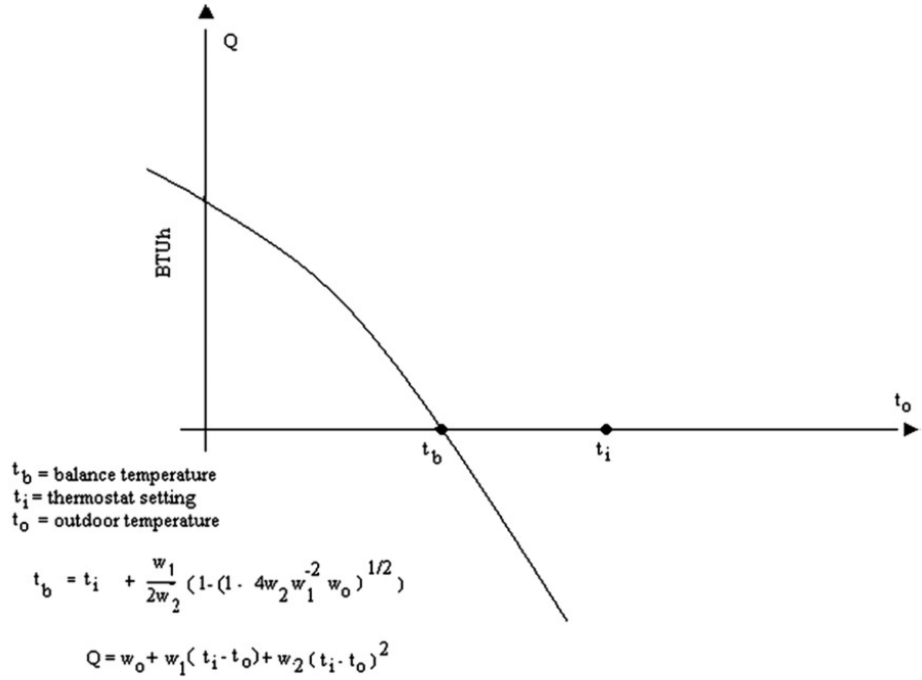

Figure 5: Thermal load function (from Dubin, 2008, Fig. 5)

Conclusions and next steps

The art and science of using climate zones in electrical load analysis are still in early stages of development. There is ample scope for BC Hydro's load research analysts to contribute to the advancement of the field.

In the Appendix discussion, the point was made that human comfort is temperature driven but building temperature is weather driven. This fundamental difference has often been minimized or ignored, often for practical reasons related to the types of weather data available to researchers. With the current need for increased precision and accuracy in load analyses, developing methods for working with an enhanced suite of weather variables is an obvious route for advancement.

Recommended next steps, based on the contents of this review, are outlined for BC Hydro's load analysis group with respect to using climate zones in load analysis. Some of the steps address the fundamental need for improving correlations between load demand and weather variables. The sequence of steps follows the topic's order of appearance in the text. Suggestions include the following:

- Evaluate whether the current four climate zones are providing the desired quality of load forecasting accuracy. Consider weighting regions by population density;
- Locate weather data less than hourly. Overcome bias for hourly data simply because it is easy to switch between energy and power (capacity) values;
- Continue testing and calibrating methods for using clustering to generate climate zones;

- Try zoning based on HDD/CDD ratios because portable air-conditioning units and evaporative cooling units are increasingly accessible to homeowners at big-box building supply retailers;
- Allow for urban heat island effects in analyses and attempt to quantify effects for major population centres in BC;
- Tabulate the many weather variables of potential use for load forecasting and quantify the relative importance of each;
- Experiment with zoning according to HDD—similar to Energy Star®—but allow up to, say, 10 zones in BC;
- Evaluate usefulness of driving rain index in predicting demand;
- Evaluate cooling potential of evaporative cooling after precipitation events and degree to which this cooling affects demand;
- Evaluate use of moisture index in predicting demand;
- Prepare to publish (for internal use) a set of climate materials;
- Evaluate use of artificial neural networks;
- Evaluate ‘dead zone’ and seasonal sensitivity of demand per climate zone as this may affect recommendations for evolution of Hydro’s electrical distribution network;
- Evaluate use of weather ensemble predictions with Taylor and Buizza’s equation for weather related demand (equation 3) which incorporated effective temperature (lag included), cooling power of wind, and cloud cover;
- Evaluate use of degree hour versus degree day (heating and cooling);
- Establish up-to-date listing of all weather station sites in BC, plot on base map, and compare to population density;
- Test whether peak loads are correlated significantly with summer convection in BC’s climate zones;
- Conduct research and development related to specialized weather information needs for load analysis [probabilistic forecasts, boundary layer meteorology, thermodynamics (of buildings), new probabilistic and statistics metrics, numerical modeling, and verification with limited data];
- Evaluate advantages to using combined or composite weather variables; and
- Evaluate use of Dubin’s equation for heat loss from a building (equation 5).

Appendix—Thermal energy demand: scientific basis

Demand is discussed first in terms of individual customers sensing the various stimuli associated with a weather event. Next, the customers react, leading to decisions and action about electrical energy use. Decisions and actions depend on properties of the building in which they live or work. Finally, the aggregate similar behaviour of those customers residing in numerous buildings in the same climate zone creates an electrical energy demand that Hydro must deliver through its electrical distribution base serving that climate zone (Figure A-1).

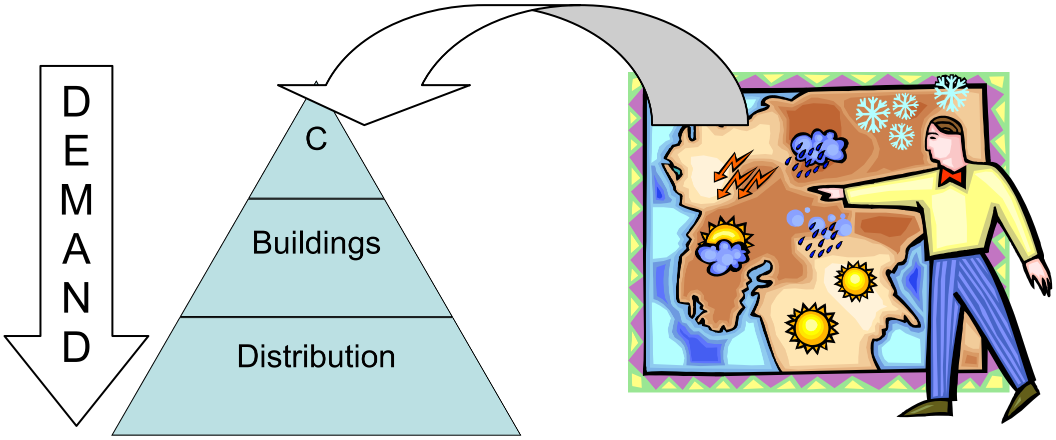

Figure A-1: Electrical demand hierarchy (C is customers responding to weather events). Demand is supported by an electrical distribution base

Thermal energy demand

Demand originates with people inside a room in a building. According to Oke (1978) their energy balance is described by the equation:

$$Q^* + Q_M = Q_H + Q_E + Q_G + \Delta Q_S \qquad [\mathrm{W\ m^{-2}}] \qquad \text{(A-1)}$$

where Q^* is net all-wave radiation flux density inside the room , Q_M is metabolic heat production by the people, Q_H is sensible heat flux density from the air in the room, Q_E is latent heat flux density inside the room, Q_G is sub-surface (ground) heat flux density in the room, and ΔQ_S is net change of body heat storage (Figure A-2). Net storage must remain close to zero for humans to maintain thermoregulation and avoid having their deep body temperature decrease or increase outside a narrow range. Practically, humans feel comfortable when ambient temperatures are in the range 20–25°C. Human comfort is temperature-driven.

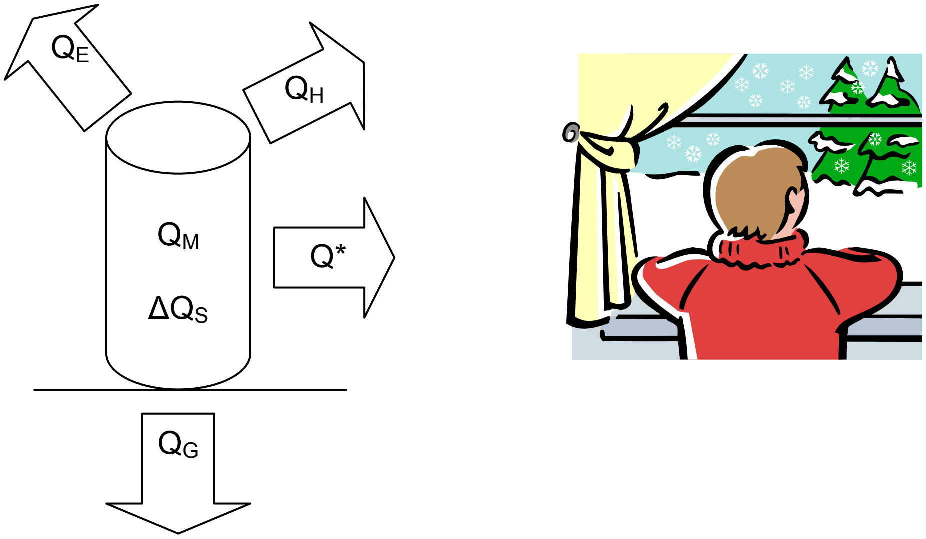

Figure A-2: Schematic of energy flux densities from a person's torso (vertical cylinder). See text for explanation of symbols (after Oke, 1978, Fig. 7.10)

The energy balance of the building (and its air volume) housing the people is, according to Oke (1978):

$$Q^* + Q_F = Q_H + Q_E + Q_G + \Delta Q_S \qquad [\mathrm{W\ m^{-2}}] \qquad \text{(A-2)}$$

where Q^* is net all-wave radiation flux density of the building envelope, Q_F is the total internal anthropogenic heat release from space heating, cooking, lighting, electrical appliances, and metabolism of humans and pet mammals, Q_H is sensible heat flux density, Q_E is latent heat flux density, Q_G is ground heat flux density, and ΔQ_S is net change of heat storage in the building materials and air volume (Figure A-3).

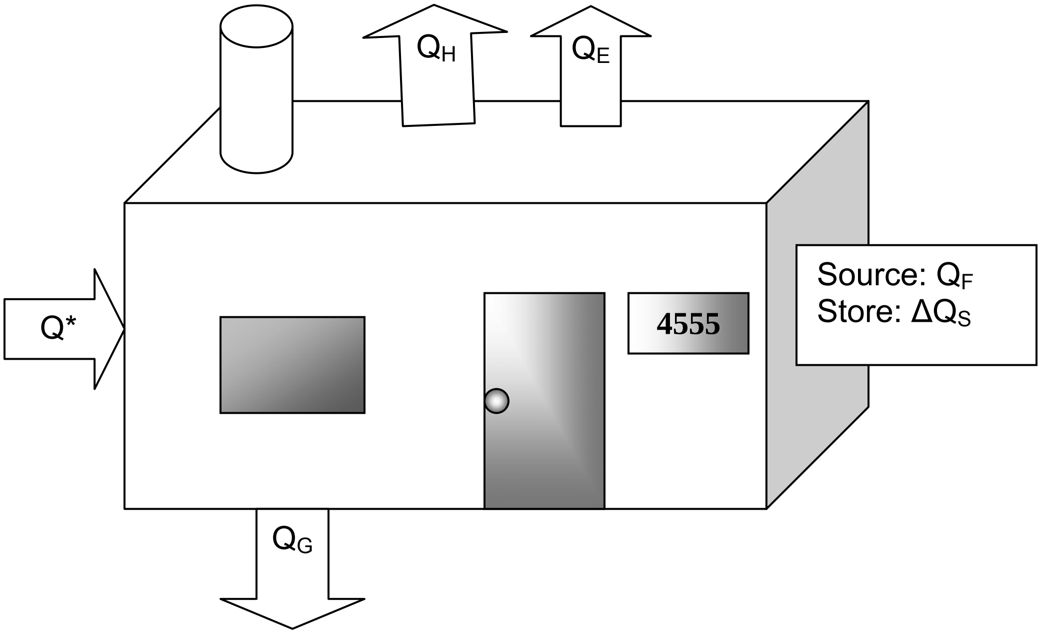

Figure A-3: Schematic of energy flux densities from a building. See text for explanation of symbols (after Oke, 1978, Fig. 7.10)

Sensible heat flux density, Q_H, from the building's exterior depends on wind speed and the thermal gradient between the inside and outside air. Evaporative heat flux density, Q_E, can be significant if the building is wet from rain or melting snow. Heat loss to the ground, Q_G, depends on how much of the building contacts the ground, the thermal properties of building materials, and the temperature gradient between building and ground. Building interior temperature is weather-driven, not only temperature-driven.

A combination of weather variables may cause a building interior temperature too low for human comfort. Q_F increases when people decide to add heat to the building's interior air volume. This action adjusts the building's energy balance which adjusts the energy balances of individual people inside the building. The net effect, for an electrically heated building, is demand for electrical energy. In practice, there is rarely enough information known about a customer's residential building to construct models based on equation (A-2). A simple model for the relationships between regional weather, energy-use decisions by customers, and demand is shown in Figure A-4.

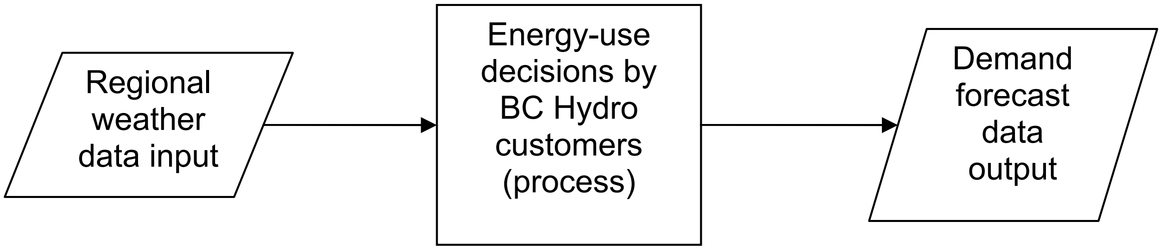

Figure A-4: A simple model for the relationships between regional weather, energy-use decisions by customers, and electrical demand

The model response, in terms of electrical energy use, of a particular building to weather variables, could be expressed by simple or multiple linear regressions. Electrical energy use against cooling degree days for a hospital building was modeled in this way in an example in ASHRAE (2005). The simple linear regression is shown in Figure A-5. This technique has been used by BC Hydro's load research analysts (Scott Albrechtsen, 2009, personal communication).

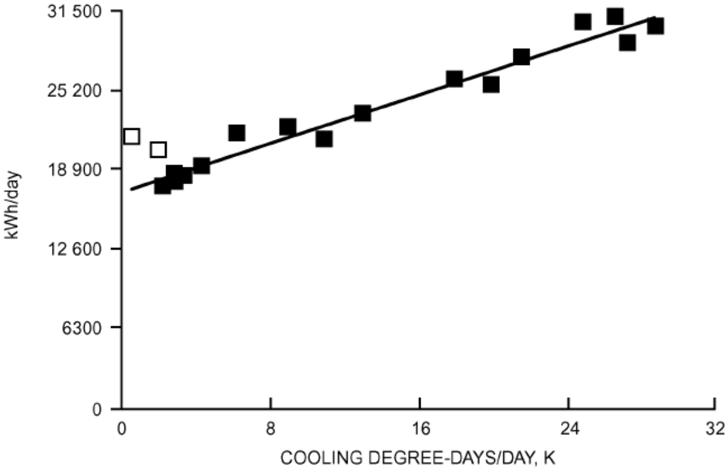

Figure A-5: Simple linear regression of daily energy use versus cooling degree-days in a hospital building (ASHRAE, 2005, p. 32.30, Fig. 19). Open squares represent data from utility bills excluded from the regression. The solid black line is the fit by the baseline equation

A simple linear regression model for a non-electrically heated single-family dwelling is shown in Figure A-6. This is a model of the response of the building's water heater and furnace motor to the single weather variable, heating degree-days per day. An unknown amount of the correlation between daily electrical consumption and HDD/day stems from the fact that lighting uses at northern latitudes increase as the weather gets seasonally colder. The HDD/day variable could be viewed as an index of composite electrical energy consumption in a household. Each building to which the linear regression model, y = mx + b, is applied will have a unique signature pair of constants for the slope (regression coefficient), m, and y-intercept (base constant), b.

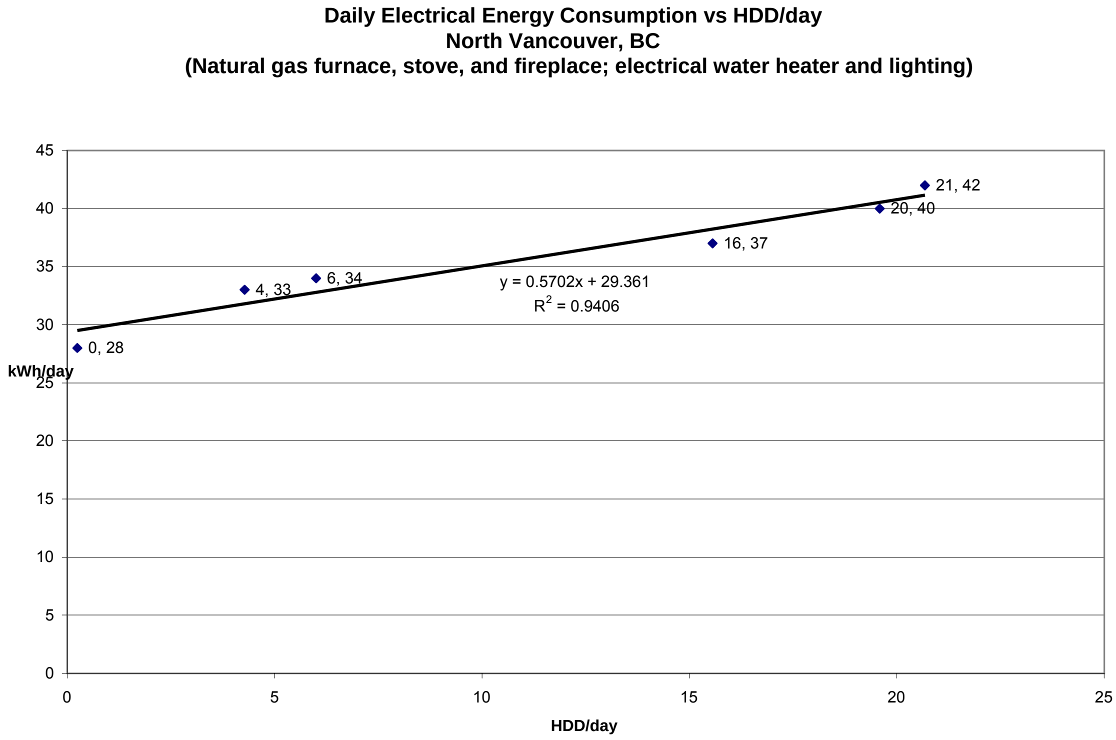
Daily Electrical Energy Consumption vs HDD/day
North Vancouver, BC
(Natural gas furnace, stove, and fireplace; electrical water heater and lighting)

Figure A-6: Simple linear regression of daily energy use versus heating degree-days in the author's single-family dwelling building. A test was performed for the hypothesis that there is zero correlation between daily electrical consumption and HDD/day for this building, at the 5% level of significance: data points, n =6; number of variables = 2; therefore, 4 degrees of freedom; coefficient of determination, R^2 = 0.9406; coefficient of correlation, R = 0.970; from a table (Arkin and Colton, 1963) of critical absolute values of correlation coefficient, R, the 5% critical point is 0.811; since 0.970 exceeds 0.811, reject the null hypothesis. Consumption information was from the account bills for the year 2008. Degree-day information was from www.weatherdatadepot.com (Weather station code YVR, Vancouver International Airport, Balance point temperature 60°F)

ASHRAE (2005, p. 32.22) supported the use of correlation methods in analysing energy consumption in buildings, using databases generated from measured data. The organization cautioned against extrapolation and inadvertent exclusion of an important feature of the building system when constructing the correlation. A statistical approach using least-squares regression is appropriate for demand side management studies (ASHRAE, 2005, pp. 32.24–32.25). A further caution was model coefficients generally have little or no physical meaning. Meaningful simulations are possible, however.

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