A Technique for Transferring Central Air Conditioning End-Use Load Shape Data

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Overview

This paper describes an initial evaluation of the load-normalization technique embodied in the California Energy Commission's (CEC) peak demand forecasting model for possible application as means for end-use load data transfer. Metered, residential central air conditioner data collected by the Pacific Gas and Electric Company (PG&E) (Pacific Gas and Electric Company (PG&E) 1987) and by the Bonneville Power Administration (BPA) are the basis for the comparison.

The goal of this paper, in addition to evaluation of the CEC technique, is to illustrate two issues that we believe will always be important for evaluations end-use load shape data transfer methods: 1) the appropriateness of evaluation methods that distinguish between energy use and load shape; and 2) the criteria used to evaluate end-use load shape transfer techniques.

We motivate the evaluation by describing the CEC load-normalization technique and its relevance for end-use load shape data transfer. We then describe the method used to evaluate the CEC technique. Finally, we present our findings and discuss their significance.

CEC Space Conditioning Load Shape Representation

The CEC relies on a series of end-use forecasting models to forecast electricity demands for each major electric utility service territory in the state of California (California Energy Commission (CEC) 1991). The peak demand forecasting model acts as a post-processor to several models, which separately forecast total annual energy consumption by sector. The object of the peak demand model is to allocate these forecasts of annual energy use by end use to the hours of the year and, in particular, to the system peak day.

For space conditioning end uses, the allocation takes place in two steps. First, annual energy use is allocated to daily energy use through the use of a lagged function of daily average temperatures. Second, daily energy use is allocated to the hours of the day through the use of a time-temperature matrix (which we will refer to interchangeably as simply the matrix). The time-temperature matrix estimates hourly energy use based on both the time of day and a measure of climatic severity, which is called a temperature-humidity index or THI.[1] Figure 1 contains a sample time-temperature matrix with a "trace" of 24 hourly THI values from a single day. Time of day increases from lower right to upper left on the X-axis. THI increases from lower right to upper right on the Y-axis. The matrix value increases from bottom to top on the Z-axis.

[1] Formally, the temperature-humidity index is defined as follows: THI = 15 + 0.4 * (DBT + WBT), where DBT = dry bulb temperature and WBT = wet bulb temperature.

With regard to the issue of end-use load shape data transfer, the time-temperature matrix is, in effect, a technique for predicting space conditioning energy use as a function of weather and time-of-day. That is, the basic idea behind the matrix is that there is a unique load shape associated with any particular 24 hour series of THIs. From the standpoint of the user of the matrix, it matters not what time of year the 24 hour THI series emerges from nor, more importantly, from what part of the service territory the temperatures are recorded.

If, in fact, the matrix fully captures the weather- and time-of-day-related influences on space conditioning energy use, then it may by an extremely powerful tool for transferring the information embodied in end-use metered space conditioning collected in one utility service territory to another. For example, by transforming end-use metered data collected in service territory A into the time-temperature matrix format, one could then estimate end use load shapes for service territory B simply by introducing hourly weather information from service territory B. The development of time-temperature matrices from existing utility end-use metered data would significantly reduce the need to collect space conditioning end-use metered data in other utility service territories.

The goal of this technical note is to evaluate the performance of the CEC matrix with respect to this hypothesis. For the present evaluation, we have chosen to restrict our examination solely to the time-temperature matrix (as opposed to evaluating the allocation of energy use to the days of the year). This choice means that we will only be able to compare air conditioner load shapes, not energy use. The implications of this choice will be discussed in reviewing our results.

Evaluating CEC Space Conditioning Matrices with Metered Data

There are three parts to the evaluation of the CEC space conditioning time-temperature matrix. The first is specification of the evaluation to be performed. The second is definition of the criteria used in the evaluation. The third is description of the data used in the evaluation.

The evaluation procedure is intended to replicate a prototypical future end-use data transfer process that might take place between utilities. In the first step, end-use metered data collected by one utility (in this case, BPA) are transformed into the format of the CEC time-temperature matrix. In the second step, the transformed matrix is combined with weather data from a second utility service territory (in this case, PG&E) to develop new load shapes. However, unlike a future data transfer between utilities, in this case, we also have end-use metered space conditioning data from PG&E. Therefore, we can directly evaluate the accuracy of the out-of-service territory matrix (developed from BPA data) in predicting in-service territory metered loads (in this case, PG&E air conditioning).[2]

The evaluation of how well the matrix performs in predicting loads is complicated by the many potential uses of end-use load shape data. We have chosen to rely on four criteria, which were developed in a separate project (Eto and Moezzi 1992). While they are not definitive, we believe they capture several of the most important issues for end-use load shape comparison: 1) the time of the peak demand; 2) the magnitude of the predicted peak demand; 3) the magnitude of load at the time of an exogenously specified system peak demand (for PG&E, 4 PM in the summer); and 4) an overall measure of comparability, which is measured using the square root of the sum of the square of each of the 24 hour differences. Figure 2 illustrates these how these criteria are measured for a load shape "predicted" by the matrix from an actual 24 hours series of THIs observed on one day and the actual loads recorded on that day.

We used three sets of data in the evaluation: 1) hourly central air conditioning end use metered data and corollary hourly weather data collected by PNL for the BPA ELCAP project (Pratt et al. 1989); 2) hourly central air conditioning end use metered data collected by PG&E in their AMP project (Pratt, Conner et al. 1989); and 3) NOAA hourly weather data corresponding to three of the regions used by CEC in forecasting PG&E loads.

The BPA ELCAP data were processed by PNL into the format of the CEC time-temperature matrix (we shall refer to this matrix as the PNL matrix). Due to the small number of appliances metered and to deal with the limited time-temperature combinations observed, a smoothing technique developed by LBL (Ruderman et al. 1989) was first applied to the PNL time-temperature matrix. Figure 3 shows the raw, un-smoothed matrix. Figure 4 shows the "smoothed" matrix. Note for ease of comparison, Figure 4 only reports smoothed values for those time-THI combinations for which measured data were observed in the original raw PNL matrix; in fact, values for un-observed combinations of time and THI are also estimated by the smoothing technique, as well (see, for example, Figure 1).

Metered central air conditioner data collected by PG&E from over 350 households for a period of five years (1985-89) were analyzed by LBL in a previous project (Eto and Moezzi 1992). For the present analysis, the weather and average load shape data for three separate regions within the PG&E service territory were used. The definitions of the regions correspond to three of the five regions used by CEC in forecasting residential loads for the PG&E service territory. The three regions correspond to the hottest parts of the central valley of California (region 3), the slightly cooler middle region of the

[2] In addition, we will also compare the performance of the matrix developed from BPA data to the performance of matrices developed previously by LBL from the PG&E data.

central valley (region 2), and the more temperate in-land, but not coastal, valleys (region 4).[3] See Figure 5.

Findings

Prior to calculation of numerical results for the four evaluation criteria, we performed a visual comparison of the PNL matrix to matrices developed by LBL in a previous project (Eto and Moezzi 1992). Figure 5 is a plot of the *differences* between the PNL matrix values and one of the matrices developed previously by LBL. If the matrices were close to identical, the differences should be small and nearly constant -- that is, a flat surface. Instead, we observe differences that increase with THI. We used this observation to create a second PNL matrix in which each matrix value is shifted linearly in THI by a constant amount (in this case, 4 degrees). Thus, the value that was assigned to, say 4 PM and THI 80 is now assigned to 4 PM and a THI of 84. We shall refer to this second matrix as the "PNL shifted" matrix. Figure 6 is a plot of the difference between the shifted matrix and the LBL matrix.

The significance of the numerical results for the four evaluation criteria described previously is enhanced by comparisons with our findings from the previous LBL analysis of the PG&E data (Eto and Moezzi 1992). That is, the numbers by themselves express the absolute level of accuracy achieved, while comparison to results generated previously by LBL express a relative level of accuracy. For each of the four criteria considered, we present results from evaluation of four separate matrices: 1) the PNL matrix (smoothed, but un-shifted); 2) a linear transformation of the smoothed PNL matrix (the PNL shifted matrix); 3) a matrix developed previously by LBL using all five years of data from all metered sites (the LBL grand matrix); and 4) matrices developed previously by LBL using all five years of data, but only those data from metered sites within a particular region (the LBL region-specific matrix). In the earlier LBL study, we found that the LBL region-specific matrices performed better than the LBL grand matrix.

Our findings are summarized on six tables. Tables 1-3 summarize results for the hottest 5% of summer days in regions 2, 3, and 4, respectively and are intended to measure the performance of the matrices for those days that would be most highly correlated with system peak days. Tables 4-6 summarize results for all summer days, where summer is defined as the months of May through October and are intended to summarize performance of the matrices over all days.[4]

[3] The central air conditioning loads for the remaining two regions within the PG&E service territory are in-significant due minimal air conditioning requirements and (consequently) low saturations of central air conditioners.

[4] We shall discuss our belief that a more restrictive definition of Summer may be warranted for future evaluations of the performance of these matrices.

The format of each table is the same. The first part of each table reports the match between the timing of the peak demand predicted by the matrix and that observed in the measured data. Specifically, we report the percentage of days for which the match was exact, one hour early, one hour late, and greater than two hours off. The next part of the table reports the difference in the magnitude of the peak load between the prediction and the measured data. Several properties of the distribution of these differences are reported, including the mean, mean absolute, and median values, and standard deviation. Note that the values reported are percentages of total daily energy use (as is dictated by the format of the CEC time-temperature matrix) and that the peaks may occur at different times of day (as indicated by the previous criteria). The third part of the table reports the differences (in the same units) for 4 PM. The final part of the table reports the RMS values for the overall load shape. (By definition, the mean is identical to the mean absolute value and so is not reported.) The number of days for which the comparisons are made is reported on the final line of each table.

It is useful to consider the results for the hottest summer days (Tables 1-3) separately from the results for all summer days (Tables 4-6). As expected, the shifted PNL matrix performs better than the original PNL matrix. In fact, the shifted PNL matrix performs better than the LBL grand matrix and often compares favorable against the LBL region-specific matrices. On an absolute basis, however, the matrices are still subject to inaccuracies. For example, with regard to the magnitude of peak demand, both the LBL region-specific and the PNL shifted matrix on average over-predict load by between 0.5 and 1.0% of total daily load. When one considers that load in the peak hour is typically 12% of total daily energy use, these over-predictions translate to 4 to 8% over-predictions of the absolute magnitude of the peak load.

With regard to the other evaluation criteria, the PNL matrix and the PNL shifted matrix both tend to predict the peak hour with greater frequency than does either LBL matrix. However, the PNL matrices tend to predict peaks one hour early with greater frequency. For the loads that are coincident with PG&E system loads (4 PM), we continue to find over-predictions by most of the matrices. For region 3, however, the LBL matrices are quite accurate and the PNL matrices under-predict loads. The RMS results are quite consistent with one another; the PNL shifted matrix has lower RMS errors than does the un-shifted PNL matrix and the values are very close to those found for the LBL region-specific matrices.

Interpreting the performance of the matrices for all summer days (Tables 4-6) is complicated the by the format of the time-temperature matrices. That is, the matrices do not yield loads in energy units (e.g., kW), but instead percentages of total daily load. This format means that a given percentage errors (between predicted and measured loads) for days on which there are insignificant cooling loads (i.e., during temperate weather) have *equal* weight with the same percentage errors on days with significant cooling loads. In other words, our examination of the CEC matrix format can only consider differences in load shape, not energy. While this is a useful analytic distinction, we know intuitively that large percentage errors on days with little or no cooling are not nearly as important as smaller percentage errors on days with significant cooling. This limitation, in fact, underlies our separate consideration of the performance of the matrices on the hottest 5% of summer days (Tables 1-3).

Hence, restricting now our attention to the load shape (not energy) results presented in Tables 4-6, we find qualitatively similar, but as expected somewhat poorer, results to those found for the hottest 5% of summer days. That is, the PNL shifted matrix performs better than does the un-shifted matrix, and in fact performs better than the LBL grand matrix. While this result is encouraging on a relative basis, consideration of the absolute values suggests that there remain measurable errors. With regard to the timing of the peak, the PNL matrices do not appear to be biased to predict peak loads either earlier or later than the measure loads and tend to predict the correct hour of peak load between 23 and 32% of the time. The results for the magnitude of the peak are somewhat better than those found for the hottest 5% of summer days, however, since peak loads on average are some what lower (in percentage of total daily energy) the relative errors may be comparable. We find somewhat poorer results for the predictions of load at 4 PM than those found for the hottest 5% of summer days. Finally, the RMS errors are also poorer than those found for the hottest 5% of summer days.

Concluding Remarks

Our main finding was that a small transformation of the PNL matrix led to results that were comparable to those found in previous LBL analyses of PG&E data. On the one hand, this finding suggests that the CEC load shape normalization may be a promising technique for central air conditioning load shape data transfer. On the other hand, this optimism should be tempered by, at least, two considerations. First, the "shift" made to the PNL matrix, which led to the improved performance, was based on a visual review of the un-shifted matrix and matrices previously developed by LBL. It is unlikely that this information would be available to a utility attempting to use a time-temperature matrix developed from metered data collected in another service territory. (We are, of course, keenly interested in techniques that might allow us to address this issue.) Second, despite performance comparable to earlier matrices developed by LBL, the absolute errors remain a source of concern. For example, peak loads are over-predicted by 4 to 8% on the hottest summer days. Moreover, and perhaps of greater concern for the use of the CEC load normalization technique is that the LBL matrices were developed from the same data that were used to examine their accuracy. That is, the evaluation of the LBL matrices were performed using data that should be the most favorable for evaluating their performance.

We, nevertheless, believe that the CEC technique provides a promising basis for future enhancements. More importantly, this review has led to the articulation of specific criteria for evaluation of end-use load shape data transfer techniques. It has also identified the evaluation of load shapes from that of energy use as a separable issue for consideration in load shape comparisons.

References

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Table 1
Comparison of Predicted Load Shapes to Measured Loads for Hottest 5% Summer Days 1985-1989 in CEC Region 2 (Sacramento)

	PNL Matrix	PNL Shifted Matrix	LBL Grand Matrix	LBL Region 2 Matrix
Timing of Peak Hour				
% same	36	34	23	17
% 1 hour late	19	28	28	15
% 1 hour early	36	26	32	34
% > 2 hours off	0	4	4	8
Magnitude of Peak (measured-predicted)				
mean	0.016	-0.007	-0.022	-0.008
mean absolute	0.016	0.011	0.022	0.011
median	0.013	-0.006	-0.020	-0.060
standard deviation	0.010	0.011	0.013	0.013
Magnitude of 4 p.m. Load (measured-predicted)				
mean	-0.001	-0.008	-0.014	-0.016
mean absolute	0.007	0.011	0.017	0.018
median	-0.010	-0.009	-0.014	-0.016
standard deviation	0.009	0.011	0.015	0.014
RMSE				
mean	0.009	0.009	0.013	0.010
median	0.008	0.008	0.013	0.010
standard deviation	0.002	0.002	0.003	0.003
Number of day pairs *47*				

Table 2
Comparison of Predicted Load Shapes to Measured Loads for Hottest 5% of Summer Days 1985-1989 in CEC Region 3 (Fresno)

Timing of Peak Hour	PNL Matrix	PNL Shifted Matrix	LBL Grand Matrix	LBL Region 3 Matrix
% same	25	38	27	27
% 1 hour late	10	23	25	25
% 1 hour early	50	27	23	25
% > 2 hours off	0	0	10	8
Magnitude of Peak (measured-predicted)				
mean	-0.022	-0.010	-0.001	-0.004
mean absolute	0.022	0.005	0.006	0.007
median	0.020	0.006	0.002	-0.004
standard deviation	0.006	0.006	0.008	0.007
Magnitude of 4 p.m. Load (measured-predicted)				
mean	0.008	0.001	0.001	-0.001
mean absolute	0.008	0.005	0.006	0.007
median	0.008	0.000	0.001	-0.001
standard deviation	0.005	0.006	0.008	0.008
RMSE				
mean	0.010	0.006	0.007	0.007
median	0.010	0.006	0.006	0.007
standard deviation	0.002	0.001	0.002	0.002
Number of day pairs 48				

Table 3
Comparison of Predicted Load Shapes to Measured Loads for Hottest 5% Summer Days 1985-1989 in CEC Region 4 (San Jose)

	PNL Matrix	PNL Shifted Matrix	LBL Grand Matrix	LBL Region 4 Matrix
Timing of Peak Hour				
% same	30	30	30	18
% 1 hour late	8	10	10	25
% 1 hour early	48	43	40	38
% > 2 hours off	0	0	3	0
Magnitude of Peak (measured-predicted)				
mean	-0.010	-0.005	-0.016	0.000
mean absolute	0.014	0.014	0.021	0.013
median	0.009	-0.008	-0.018	0.002
standard deviation	0.018	0.015	0.021	0.018
Magnitude of 4 p.m. Load (measured-predicted)				
mean	-0.005	-0.009	-0.020	-0.006
mean absolute	0.011	0.014	0.022	0.012
median	-0.005	-0.007	-0.018	-0.006
standard deviation	0.018	0.015	0.018	0.015
RMSE				
mean	0.010	0.011	0.014	0.011
median	0.010	0.010	0.014	0.010
standard deviation	0.004	0.003	0.004	0.003
Number of day pairs	*40*			

Table 4
Comparison of Predicted Load Shapes to Measured Loads for all Summer Days 1985-1989 in CEC Region 2 (Sacramento)

	PNL Matrix	PNL Shifted Matrix	LBL Grand Matrix
Timing of Peak Hour			
% same	28	27	27
% 1 hour late	18	19	18
% 1 hour early	21	20	21
% > 2 hours off	22	21	20
Magnitude of Peak (measured-predicted)			
mean	0.013	-0.004	-0.022
mean absolute	0.036	0.033	0.038
median	0.018	0.000	0.017
standard deviation	0.043	0.044	0.047
Magnitude of 4 p.m. Load (measured-predicted)			
mean	-0.013	-0.013	-0.026
mean absolute	0.029	0.029	0.037
median	-0.010	-0.010	-0.021
standard deviation	0.037	0.038	0.042
RMSE			
mean	0.026	0.026	0.029
median	0.022	0.021	0.023
standard deviation	0.015	0.016	0.017
Number of day pairs 920			

Table 5
Comparison of Predicted Load Shapes to Measured Loads for all Summer Days 1985-1989 in CEC Region 3 (Fresno)

	PNL Matrix	PNL Shifted Matrix	LBL Grand Matrix
Timing of Peak Hour			
% same	32	32	31
% 1 hour late	16	22	22
% 1 hour early	22	17	16
% > 2 hours off	18	21	19
Magnitude of Peak (measured-predicted)			
mean	0.016	0.002	-0.010
mean absolute	0.031	0.024	0.026
median	0.024	0.007	-0.001
standard deviation	0.033	0.033	0.037
Magnitude of 4 p.m. Load (measured-predicted)			
mean	-0.005	-0.003	-0.011
mean absolute	0.017	0.017	0.021
median	0.000	0.000	-0.006
standard deviation	0.024	0.023	0.027
RMSE			
mean	0.021	0.020	0.021
median	0.016	0.014	0.014
standard deviation	0.013	0.015	0.017
Number of day pairs 920			

Table 6
Comparison of Predicted Load Shapes to Measured Loads for all Summer Days 1985-1989 in CEC Region 4 (San Jose)

	PNL Matrix	PNL Shifted Matrix	LBL Summer
Timing of Peak Hour			
% same	25	23	26
% 1 hour late	16	19	15
% 1 hour early	25	18	26
% > 2 hours off	17	20	17
Magnitude of Peak (measured-predicted)			
mean	0.010	0.002	-0.016
mean absolute	0.029	0.029	0.033
median	0.014	0.005	-0.012
standard deviation	0.036	0.037	0.042
Magnitude of 4 p.m. Load (measured-predicted)			
mean	-0.007	-0.006	-0.022
mean absolute	0.023	0.024	0.033
median	-0.007	-0.004	-0.021
standard deviation	0.029	0.030	0.033
RMSE			
mean	0.023	0.024	0.025
median	0.020	0.021	0.021
standard deviation	0.011	0.012	0.014
Number of day pairs 731			

Figure 1. Time-Temperature Matrix

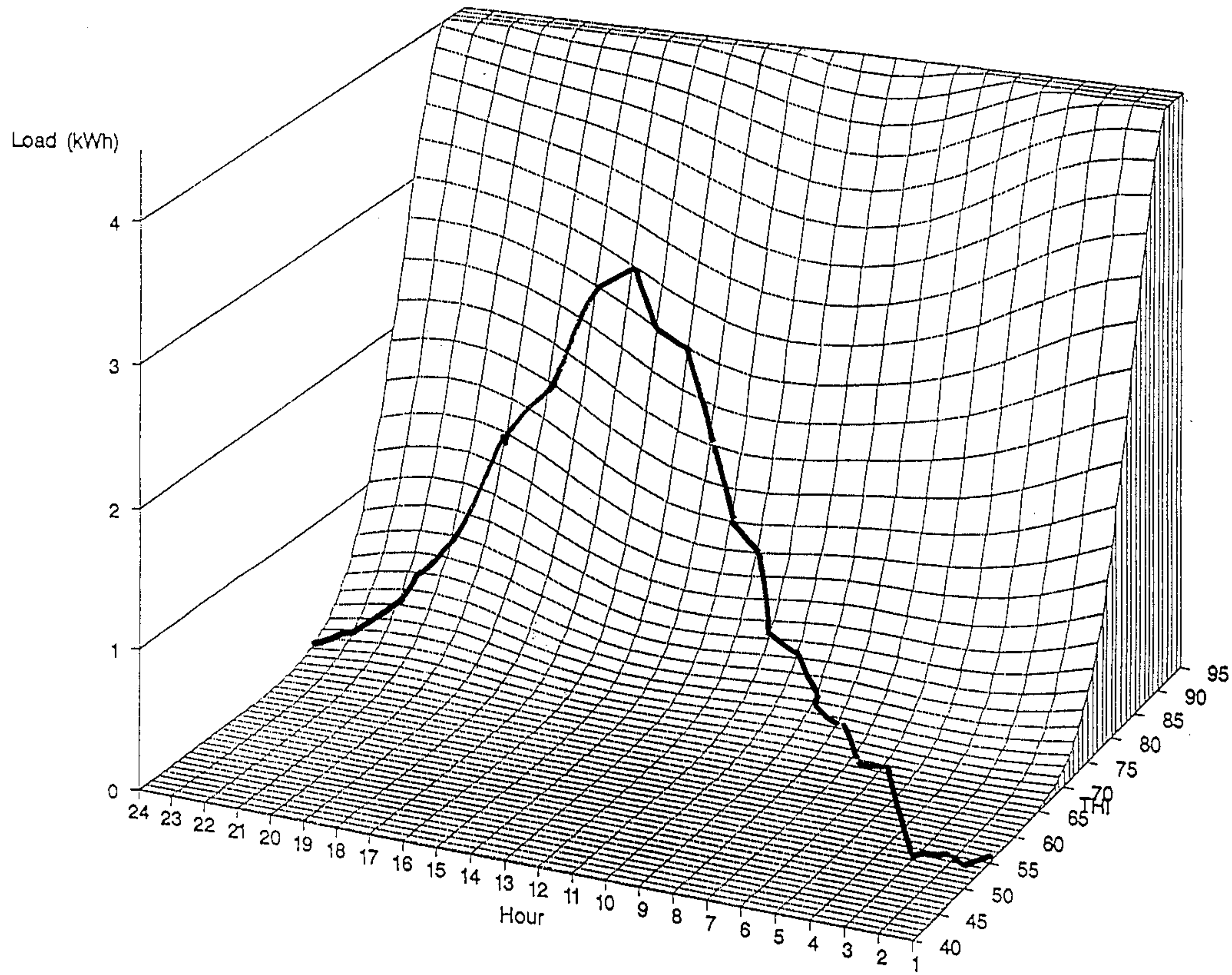

Figure 2. Raw Time-Temperature Matrix

THI = 15 + 0.4 (dry-bulb temp. °F & wet-bulb temp. °F)

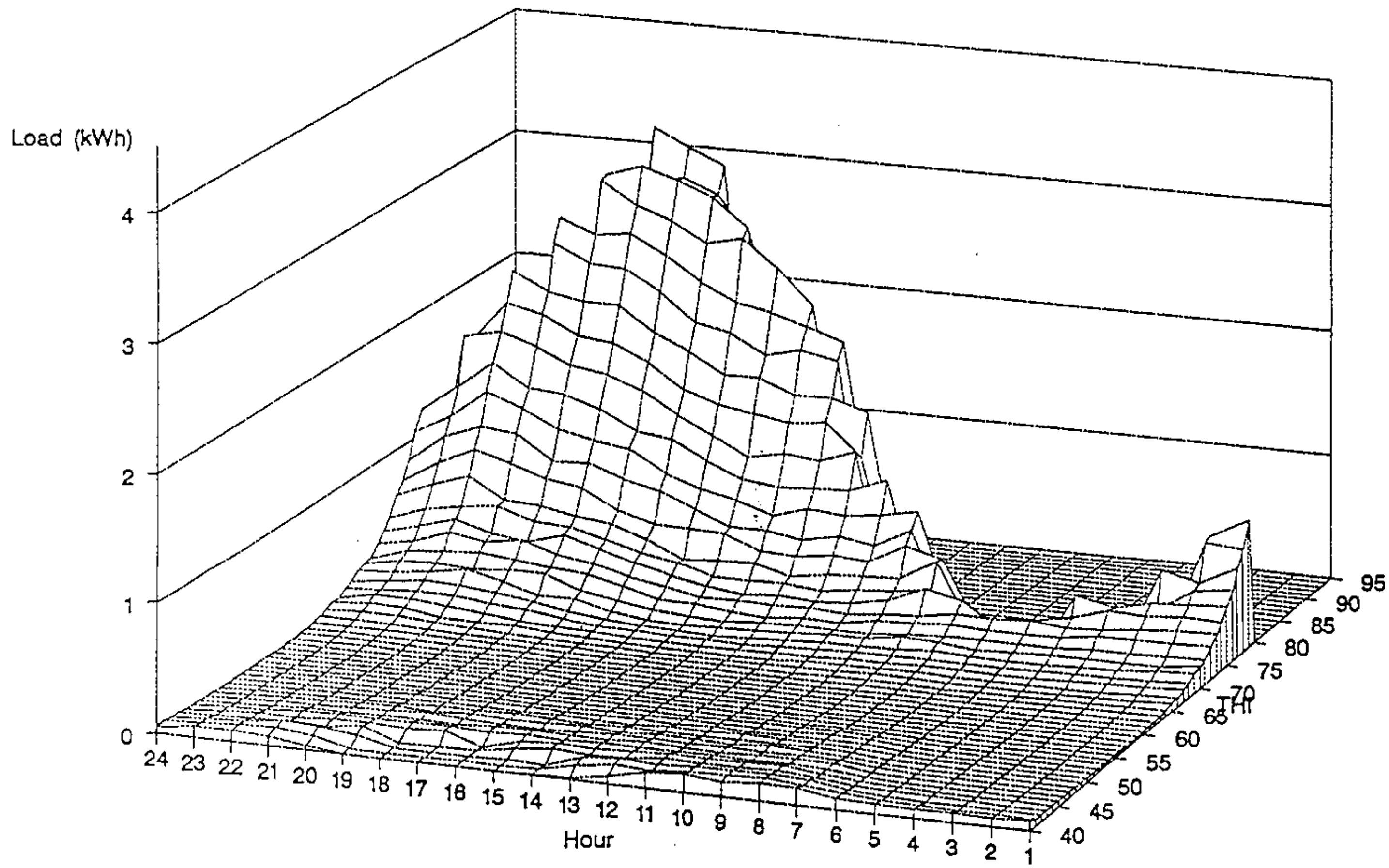

Figure 3. Smoothed Time-Temperature Matrix

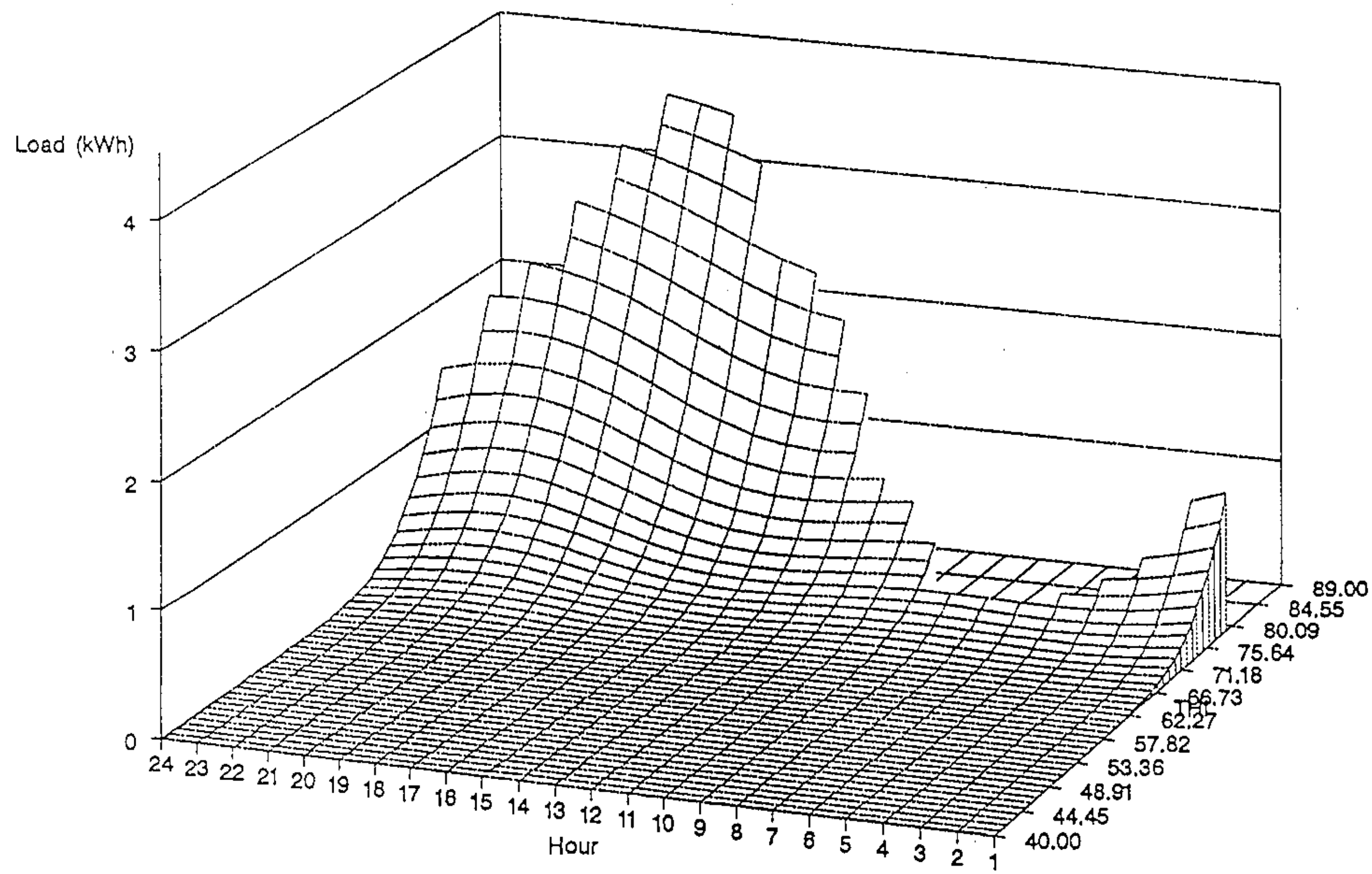

Figure 4. Measures Used to Compare Load Shapes

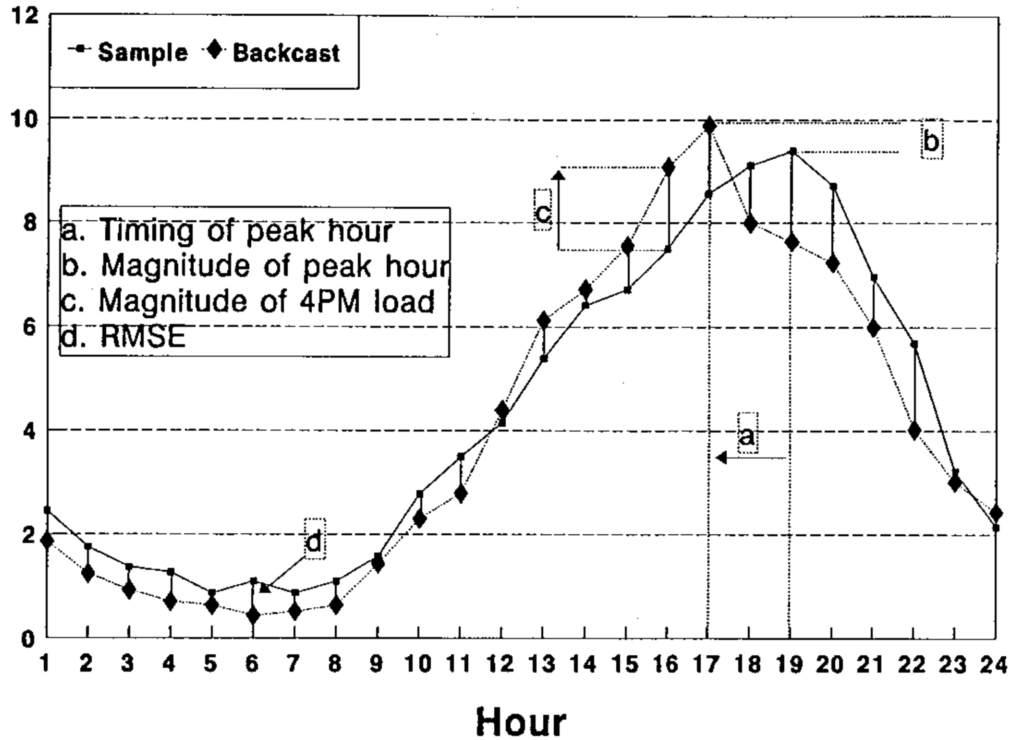

Figure 5. Climate Regions in PG&E Service Territory

Figure 6. PNL Pure AC Matrix * SHIFTED + 0 in THI * - LBL ex.matreg3 [raw]

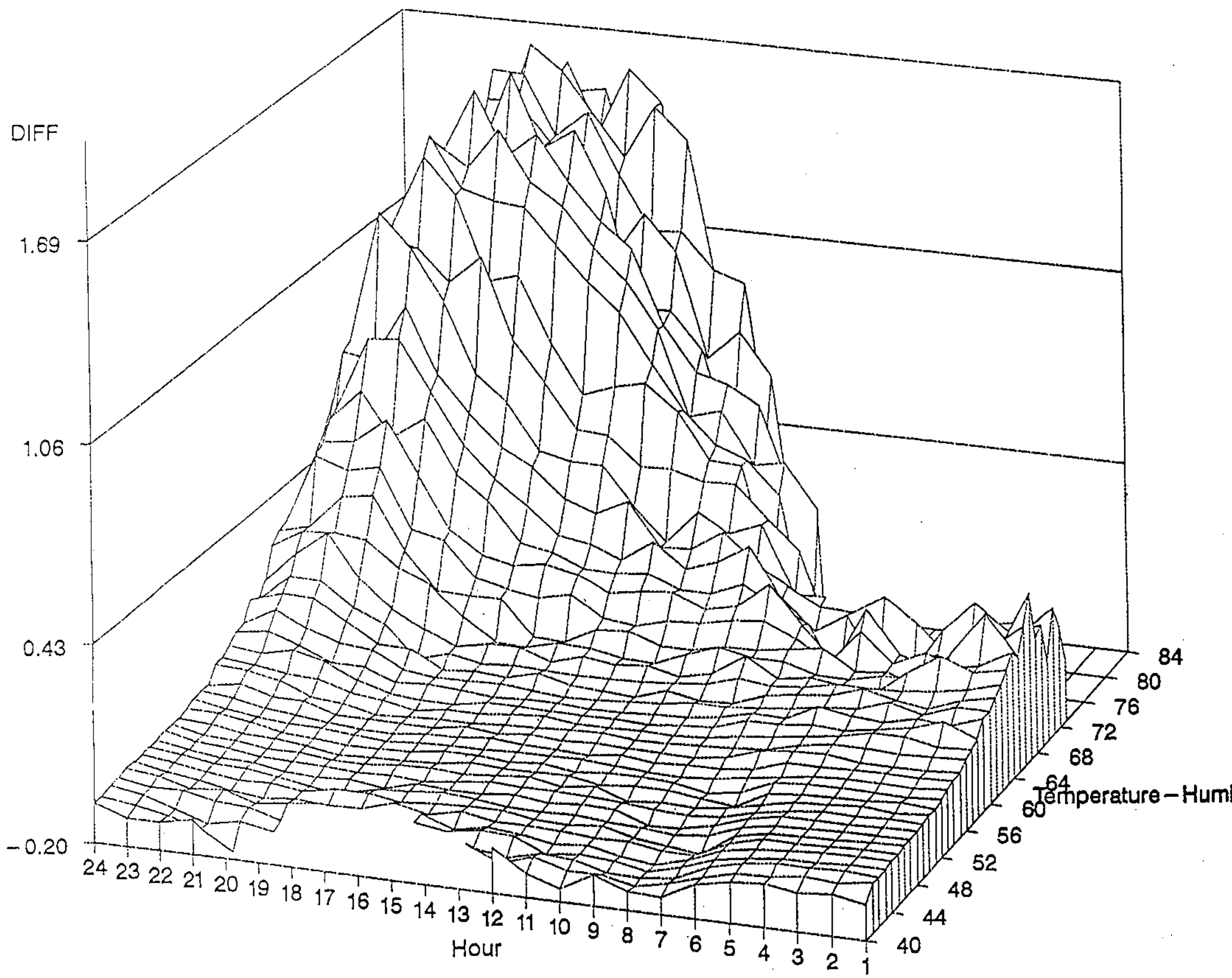

Figure 7. PNL Pure AC Matrix* SHIFTED + 4 in THI * - LBL ex.matreg3 [raw]