Modeling the Impact of Summer Temperatures on National Electricity Consumption

DOUGLAS M. LE COMTE AND HENRY E. WARREN

Center for Environmental Assessment Services, NOAA, Washington, DC 20235

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ABSTRACT

National population-weighted weekly degree day totals, which have been used to model and assess temperature-related natural gas consumption, are compared with summertime electricity consumption. A very close relationship between national cooling degree days and electricity consumption is found. A multiple regression equation depicting the relationship is developed. This model can be used to assess the impact of current weather anomalies and projected weather or climate changes on electricity use, as well as the impact of various national conservation measures, directives, or laws on temperature-related electricity use.

1. Introduction

Degree day statistics have been used for years to assess the need for indoor heating or cooling, with 65°F (18.3°C) as the base commonly used for both heating (*HDD*) and cooling degree day (*CDD*) computations. *CDD*'s for a day are the positive departure of mean daily temperature from the base. The mean daily temperature is the average of the daily maximum and minimum temperature. A daily maximum of 90°F (32°C), for example, and a daily minimum of 70°F (21°C) would yield a mean temperature of 80°F (27°C), or 15 *CDD*'s. It is hypothesized that the rate of energy use for space cooling (air conditioning) per *CDD* is constant so that *CDD*'s can be summed over time.

The possibility of an excess demand for energy for heating or cooling in the United States makes it important to quantify the relationship between temperature anomalies and energy demand.

Recently, population-weighted *HDD*'s have been used to model natural gas consumption for space heating (Lehman and Warren, 1978). Projections of gas consumption are routinely published during the heating season by NOAA's Center for Environmental Assessment Services (CEAS). The model uses population-weighted *HDD*'s provided by the National Weather Service's Climate Analysis Center (CAC) for each state and region in the contiguous United States. Additionally, since weather projections can yield energy demand projections (Quayle and Diaz, 1980), the 30- and 90-day temperature outlooks provided by CAC are used to estimate *HDD*'s and natural gas demand for the remainder of the heating season.

In this study, national population-weighted *CDD* statistics were used to examine the relationship between cooling season temperatures and electricity output. Population weights for degree day computations are calculated by first linking climatically similar counties with nearby first-order weather stations, then totaling the county populations that are climatically represented by each weather station. These county population totals are compared against the state population and proportioned accordingly. Using the state data, degree days for nine regions in the contiguous United States are determined according to the proportion of a population in a state. To determine national degree day values, the regions are weighted by the same procedures.

Degree days and other weather variables have been used to estimate electricity loads for areas served by individual utilities (e.g., Proctor, 1980), but research on national electric output, using population-weighted *CDD*'s, has been neglected. This study takes a broad perspective, using only parameters pertaining to the entire contiguous United States.

2. Data

The National Climatic Center provided daily station data from which weekly national population-weighted *CDD* totals were calculated for May–September for 1977, 1978 and 1979. The weekly figures are routinely published as Monday through Sunday totals by CEAS, but Sunday through Saturday totals were used for this study to make these figures compatible with published electricity data.

Electricity use data were based on the totals provided by the Edison Electric Institute (EEI). Each week EEI reports the net amount of electrical energy, in millions of kilowatt-hours, distributed by the Total Electric Utility Industry for the week ended on Saturday. National and regional totals are given, though only the national (48 contiguous states) data were used in this study. The sources of electric generation

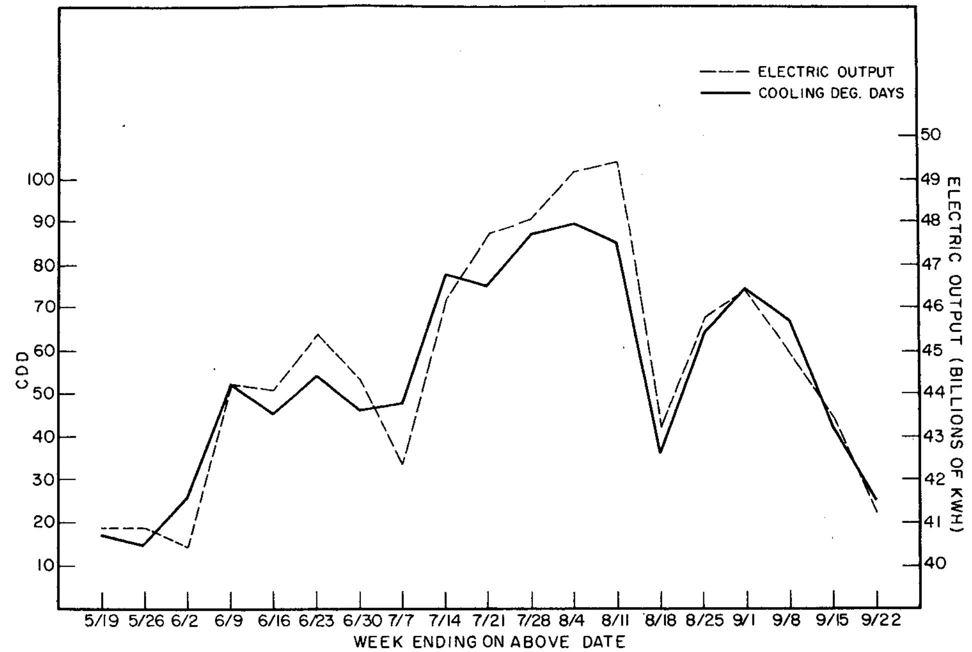

FIG. 1. 1979 weekly U.S. electric output and population-weighted cooling degree days (*CDD*).

included in these statistics include all plants "commonly referred to as contributing to the public supply" (EEI, 1978).

3. Analysis

Weekly *CDD*'s were compared with weekly electric output during 1977, 1978 and 1979. Fig. 1 illustrates the week-by-week changes in these two parameters during 1979.

Weekly electric output is seen to follow *CDD* totals rather closely. The 40 *CDD* total, for instance, appears to roughly approximate an electric output of 43 billion kilowatt-hours, with a change of 10 *CDD*'s equivalent to a change in electric output of about one billion kilowatt-hours. There are several instances, however, where discrepancies occur between *CDD*'s and electric output. For instance, during the weeks ending 2 June, 7 July and 8 September, electric output is low relative to temperature. This discrepancy—also noted during other years—is due to the Memorial Day, Independence Day and Labor Day holidays. Because of closed businesses on Monday holidays, electricity use is significantly lessened. Apparently, anomalous temperatures have considerably less impact on electricity use during a weekend than during a weekday. However, in this study the authors do not discriminate between *CDD*'s occurring on weekends and weekdays. This could account for some of the variation in the electricity data not explained by the weekly sum of *CDD*'s.

TABLE 1. Weekly national electric output, *E* (billions of kWh), as a function of population-weighted cooling degree days (*CDD*).

Year	Equation	R^2	Rmse*
1977	$E = 36.129 + 0.110CDD$	0.95	0.567
1978	$E = 37.329 + 0.121CDD$	0.91	0.694
1979	$E = 38.827 + 0.111CDD$	0.91	0.698

* Root-mean-square error.

Nevertheless, weekly *CDD*'s account for much of the variation in electric output. Statistical results were computed using the SAS software package (Barr *et al.*, 1976). Table 1 presents linear regression equations for each of the three years used in this study. These equations—omitting the holiday weeks and weeks with less than 30 *CDD*'s—reveal that *CDD*'s explained at least 91% of the variation in weekly electric output. The correlation between *CDD*'s and electric output was significant at the 0.1% level for each of the three years. It is noted that for each year the slope of the regression line remained basically the same. The intercept value (base electricity consumption) changed each year, increasing by 3% in 1978 and 4% in 1979. This value changes each year due to growth in the number of customers, growth (or lack of growth) in the economy, and other non-weather-related factors.

Because approximately 40% of all electricity consumed is used by large industrial customers, the level of industrial production will affect the level of electricity production. One can get an indication of the effect of economic conditions relative to weather by comparing the changes in total industrial production with total electricity production. Indices for both quantities are routinely provided by the U.S. Department of Commerce. The industrial production index for the May–September period increased approximately 6% per year from 1977 to 1979. The electric utility production index increased at a 2% rate during the same period. However, during the summer of 1980, when a severe heat wave took place, as well as a slowdown in industrial activity, the industrial production index declined by 7%, while the electricity production index increased by 4%. Consequently, extreme heat can increase demand for electricity more than enough to offset a decrease in demand due to economic conditions.

The equations indicate that during a typical summer week (75 *CDD*'s), temperature-related energy output (air conditioning) accounts for approximately 17% of total electric output. During a heat wave, when the *CDD* total may reach 90, cooling demand accounts for ~20% of total electric output.

The equations were combined and other variables were tested to see if the results could be improved. It was found that adding the previous week's *CDD* total to the equation reduces the mean square error. The physical reasoning behind this additional variable is that cooling requirements are affected by previous heat buildup as well as current outside temperatures. An example is the office building which is uncomfortably warm Monday morning because of heat buildup during the preceding weekend. Air conditioning use is, therefore, not only a function of current temperature, but the previous week's temperature as well. Additionally, "dummy" variables were utilized in the equation to account for changes in base consumption in 1978 and 1979 and also to account for decreased cooling demand during holiday weeks. It was found that a Monday holiday resulted in a weekly decrease in electric output of approximately 1.77 billion kWh. This decrease is quite substantial, representing a saving of ~4% on the nation's weekly electric bill.

The final equation is shown in Table 2. The square of the multiple correlation coefficient is a remarkably high 0.96. The root-mean-square error (rmse) is 0.544. Fig. 2 shows the actual and the modeled weekly electric output during 1979.

TABLE 2. Weekly electric output, combined equation.

Equation:

$$E = a_0 + a_1\,CDD + a_2\,CDD_{(-1)} + a_3Y_1 + a_4Y_2 - a_5H$$

Variables:
- E = weekly national electric output (billions of kwh)
- CDD = weekly national cooling degree day total
- $CDD_{(-1)}$ = previous week's national cooling degree day total
- H = holiday factor = 1 during holiday weeks = 0 during regular weeks
- Y_1 = 1978 growth factor = 1 in 1978 = 0 other years
- Y_2 = 1979 growth factor = 1 in 1979 = 0 other years

Coefficients:
- a_0 = 35.664 (0.295)*
- a_1 = 0.098 (0.005)
- a_2 = 0.02 (0.005)
- a_3 = 1.86 (0.177)
- a_4 = 2.765 (0.186)
- a_5 = 1.77 (0.209)

$RMSE$ = 0.544

R^2 = 0.96

All coefficients are significant at the 1% level.

* Standard error of the coefficient.

4. Use of the model

A model of the kind developed here can be put to various practical uses, among which could be 1) assessing the impact of conservation and governmental policies/directives on electricity use, 2) measuring the impact of unusual weather, e.g., a heat wave, on the economy and 3) quantifying the impact of projected climate change on electricity use and energy supplies.

As an example of an attempt to measure the impact of governmental directives on electricity use, the model was used to determine if President Carter's thermostat controls issued 16 July 1979 had a significant effect on air conditioning use. A "dummy" variable was included in the 1979 regression equation for the weeks following the issuance of the directive. The resulting coefficient of the new variable was tested and found to be not significant at the 5% level. Given the standard error of the estimated coefficient, a subsequent consumption decrease of at least 1.5% would have been significant at the 5% *t*-level. It therefore appears that no substantial change in air condition use occurred after 16 July.

Another example of an application of the model occurred during the summer of 1980. CEAS was preparing a special report on the cost of the 1980 heat wave, and the regression equation was used to estimate additional electricity demand caused by the abnormally high temperatures. Long-term mean weekly *CDD*'s were inserted in the equation and the resulting calculated "normal" weekly electric output was compared with observed output as supplied by EEI. The additional electric output above the "normal" output was multiplied by the cost per kilowatt-hour of electricity to arrive at an approximation of the national cost of the extra electricity used. This sum was found to be near one billion dollars.

In this case, the 1980 equation used the 1979 base consumption value (intercept term), as initial 1980 data from the Edison Electric Institute indicated this assumption to be reasonable. During a time of economic expansion, this assumption would give inac-

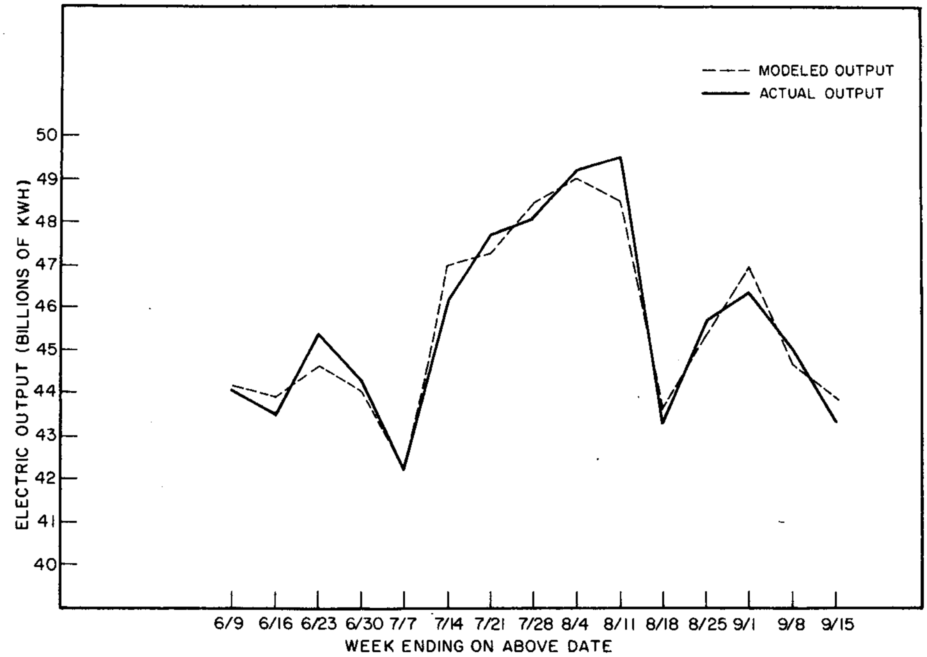

FIG. 2. Actual and modeled electric output, 1979.

curate results. During a recession, however—as was the case in 1980—base consumption would be expected to level off or even decline.

Great care must be exercised in estimating base consumption. Changing life styles and economic conditions make all projected energy-temperature relationships risky, especially beyond one year (McQuigg, 1975). A study relating peak hourly loads to daily temperatures (Johnson *et al.*, 1969) in the midwest during the 1960's showed electric demand becoming increasingly sensitive to temperatures over a period of several years. This change may have been

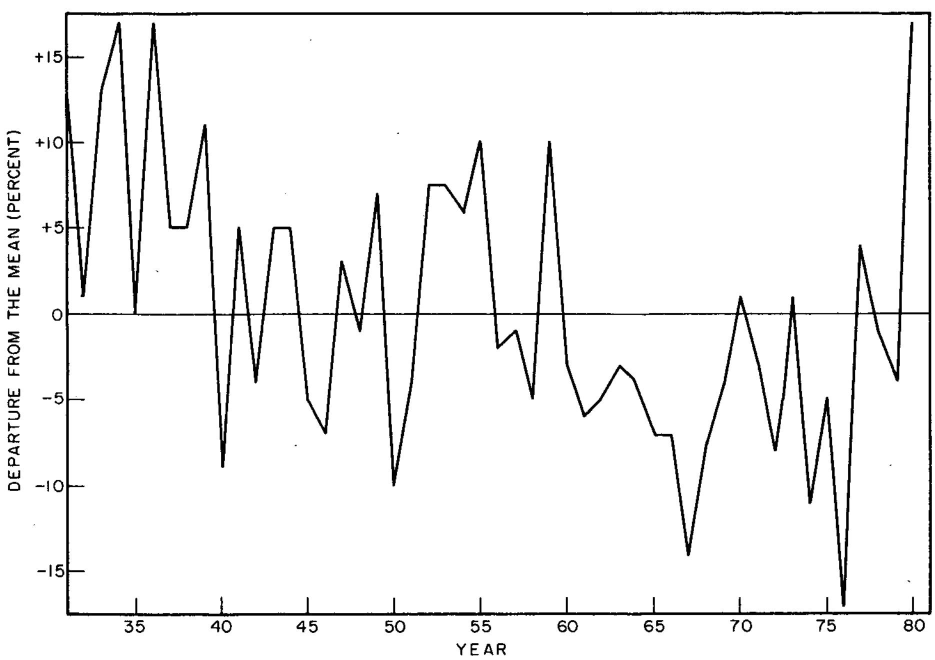

FIG. 3. Annual U.S. population-weighted cooling degree days, percent departure from the mean, 1931–80. Values for 1979 and 1980 are estimates.

largely a result of increased installation of air conditioners in homes and businesses during these years. More recently, preliminary data for 1980 indicate that electricity use during the severe heat wave in the central and eastern United States was greater than would be expected using the assumption of a stagnant or recessionary economy. In this case, a suddenly rebounding economy may have affected the energy-temperature relationship established earlier in the cooling season.

Given appropriate estimates of base electricity consumption, future energy demands and costs could be estimated for various climate scenarios using the *CDD*/electricity model. Fig. 3 shows five decades of annual *CDD* percent deviations from the mean. The climate fluctuations illustrated in this record range from relative warmth in the 1930's to coolness in the 1960's, with annual *CDD*'s averaging some 9% greater than the mean in the former case, and 6% less than the mean in the latter case. If a projected climate scenario called for a warming similar to that of the 1930's, then *CDD* totals similar to those of the 1930's could be incorporated into the model to estimate additional costs and energy needs arising from the climate change.

5. Conclusions

A simple linear regression model using weekly population-weighted *CDD* totals explained at least 91% of the variance of national electric output during 1977, 1978 and 1979. A combined multiple regression equation with additional variables for holidays, preceding temperatures, and annual changes in base electricity consumption explained 96% of the variance.

Principal shortcomings of the model include the difficulty of determining current and future base electricity consumption and the lack of discrimination between weekends and workdays inherent with 7-day temperature data.

The former problem can be somewhat alleviated if current electricity data are available for at least a short period of time, enabling estimates of the equation's intercept term to be made. It is also possible that any of various national economic indices, e.g., "real" GNP, can be used to assess the current or future state of the economy and, therefore, changes in base electric output.

Separating *CDD* totals into weekday and weekend components would alleviate the other problem, and this can certainly be done if daily *CDD* data are available.

Models can also be developed for regions and states, as well as the contiguous U.S., and this would be practical in many instances. Additionally, long-range forecasts and climatology can be used to estimate future degree days and, therefore, warm season electricity use for the next month or longer, as is currently done with the natural gas models.

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