Daily Air Temperature and Electricity Load in Spain

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ABSTRACT

Weather has a significant impact on different sectors of the economy. One of the most sensitive is the electricity market, because power demand is linked to several weather variables, mainly the air temperature. This work analyzes the relationship between electricity load and daily air temperature in Spain, using a population-weighted temperature index. The electricity demand shows a significant trend due to socioeconomic factors, in addition to daily and monthly seasonal effects that have been taken into account to isolate the weather influence on electricity load. The results indicate that the relationship is nonlinear, showing a ''comfort interval'' of $\pm 3°C$ around 18°C and two saturation points beyond which the electricity load no longer increases. The analysis has also revealed that the sensitivity of electricity load to daily air temperature has increased along time, in a higher degree for summer than for winter, although the sensitivity in the cold season is always more significant than in the warm season. Two different temperature-derived variables that allow a better characterization of the observed relationship have been used: the heating and cooling degree-days. The regression of electricity data on them defines the heating and cooling demand functions, which show correlation coefficients of 0.79 and 0.87, and predicts electricity load with standard errors of estimate of $\pm 4\%$ and $\pm 2\%$, respectively. The maximum elasticity of electricity demand is observed at 7 cooling degree-days and 9 heating degree-days, and the saturation points are reached at 11 cooling degree-days and 13 heating degree-days, respectively. These results are helpful in modeling electricity load behavior for predictive purposes.

1. Introduction

Many economic activities are exposed to weather changes, so that expected revenues may be seriously affected by a departure from ''usual'' weather. The energy sector is one of the most sensitive to weather, particularly electricity production, given that electricity cannot be stored. This fact implies that produced electricity must be instantly consumed, so a good model to predict future consumption is needed.

The high degree of uncertainty in the prediction of future electricity loads may cause significant economic losses, especially in a deregulated market—as the Spanish electricity market has been since 1998. This risk leads to the use of some kinds of financial products to compensate for future possible losses. Financial derivatives, such as futures and options contracts on electricity, are commonly employed with this objective (Pilipovic 1998).

To use and to perform a precise valuation of these kinds of financial instruments, a comprehensive analysis of the relationship between electricity consumption and weather variables, especially air temperature, must be undertaken. This work studies this relation in Spain. The paper is structured as follows. The next section gives a description of the data used in the study, and the relationship between electricity demand and temperature is analyzed in section 3. Section 4 introduces the heating and cooling degree-day variables, which allow a better characterization of the observed relationships. The final section summarizes the most relevant conclusions drawn from the study.

2. Data description

a. Electricity consumption in Spain

A series of daily electricity loads E (MW h), spanning the period from January of 1983 through April of 1999,

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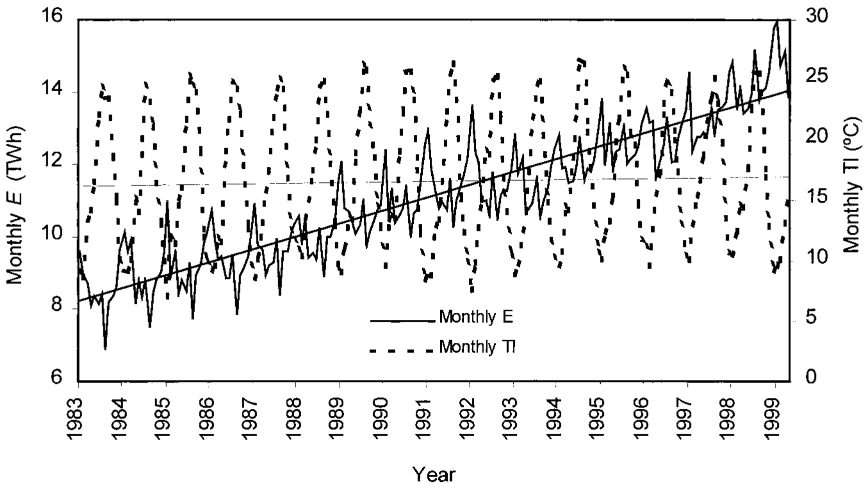

FIG. 1. Evolution of monthly electricity demand E and temperature index TI from 1983 through 1999. The trend line for each series is also shown.

has been used in the study. The data comprise the electricity consumption in all economic sectors (industrial, residential, and commercial) for all of peninsular Spain, because regional or sectorial disaggregated data were unavailable.

Electricity demand shows a significant, increasing trend that can be linked to demographic, social, and economic factors (see Fig. 1). The inspection of the series reveals two clear seasonal effects, one monthly and another daily, which can be analyzed with the monthly and daily seasonal variation indices (MSVI and DSVI, respectively). MSVI is defined as

$$\mathrm{MSVI}_{ij} = E_{ij}/\overline{E}_j, \tag{1}$$

where MSVI_{ij} is the index value for month i in year j, E_{ij} is the monthly electricity consumption for month i in year j, and $\overline{E}_j$ is the monthly average electricity load for year j. Figure 2 shows the average, maximum, and minimum MSVI values for each month of the year. The average MSVI summarizes the relative behavior between months shown by electricity consumption for the whole sample, whereas the difference between the maximum and minimum values reveals the deviations from this mean behavior. The monthly seasonality presents a maximum electricity demand in January, which decreases until May. Then, the electricity demand begins to increase from the use of air conditioning systems until September, except for a significant fall in August. The large dip in consumption in this last month is due to the significant reduction of economic activity, because most people in Spain are on summer holidays in this month. The electricity load decreases slightly in October, the transition between summer and winter, and finally in November and December it again increases from the use of electric heating appliances.

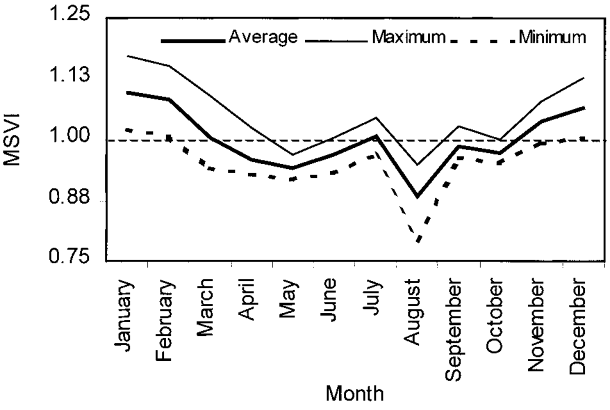

FIG. 2. Monthly seasonal profile (MSVI) for electricity demand from 1983 through 1998.

The daily index is similarly defined as

$$\mathrm{DSVI}_{ijk} = E_{ijk}/\overline{E}_{jk}, \tag{2}$$

where DSVI_{ijk} is the DSVI value for day of week i (from Monday to Sunday) in week j of year k, E_{ijk} is the electricity consumption for this same day, and $\overline{E}_{jk}$ is the daily average electricity load for week j in year k. Figure 3 shows the mean, maximum, and minimum DSVI values for each day in a week calculated from the whole sample. The electricity demand falls on Saturday and more so on Sunday. The electricity load is systematically lower on Monday in relation to the other working days, because of the inertia caused by the economic activity reduction over the weekend. Electricity load also decreases for holidays placed from Monday to Friday; this also affects the working day after a holiday and working days located between two holidays. This last effect can be appreciated in Fig. 3, in which the minimum DSVI for working days has a low value, similar to those for Saturday and Sunday. In addition, the minimum DSVI curve for those days is more separated from the average curve than the minimum values for the weekend.

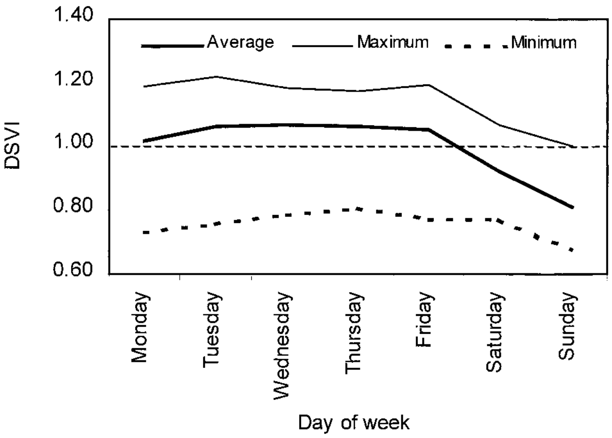

FIG. 3. Daily seasonal profile (DSVI) for electricity demand from 1983 through 1998.

b. The weather variables

Previous studies have shown that air temperature is the most significant weather variable affecting electricity demand, whereas other variables (humidity, wind speed, etc.) may be correcting terms for the influence of temperature (Engle et al. 1992; Li and Sailor 1995; Cancelo and Espasa 1996; Yan 1998). As a consequence, we have analyzed only the impact of temperature on electricity consumption, and the possible influence of other variables in the Spanish load is left for future work.

The selected variable is the mean daily air temperature (°C), because it can better capture the thermal oscillation within a day—maximum and minimum temperatures would be more adequate to analyze the existence of electricity consumption peaks or valleys. The mean daily temperature has been calculated as the arithmetic mean of the maximum and minimum daily temperatures. The use of higher-frequency data (temperature measurements each 10 or 30 min, for instance) would yield more exact estimations of the mean temperature. However, they show important limitations: 1) there are no such data series in Spain before 1990 and 2) there may be data losses in automatic weather stations. Because it is more practical to use daily maximum and minimum temperatures, we have estimated the possible error in using this approach. For this estimate, a series of temperature values taken at intervals of 30 minutes from 1992 to 1999 was used. The mean daily temperature was calculated as 1) the average of the 48 half-hourly values and 2) the arithmetic mean of the daily maximum and minimum values. Small differences were obtained between the two procedures, as can be seen in Table 1. The use of the arithmetic mean of the daily maximum and minimum temperatures does not produce a significant systematic error ($\overline{\Delta T} = 0.0°\text{C}$), whereas the random error is $\sigma(\Delta T) = \pm 0.4°\text{C}$. Thus, the procedure used is a reasonably good approximation, as has been reported by other analyses (World Meteorological Organization 1983).

Because the available electricity consumption data are not regionally disaggregated, a population-weighted temperature index TI (°C) has been constructed from the mean daily temperatures measured at four weather stations distributed across Spain, namely, Madrid (central Spain), Bilbao (north), Valencia (east), and Seville (south). The reason why population has been selected as weighting factor is that climate influences the electric consumption through the response of people to weather. That is, depending on the coldness, or heat, of weather, people will increase or decrease the use of electric heating appliances or air conditioners. Thus, the higher the population, the higher the influence of weather conditions in electricity demand.

Figure 4 shows the location of the selected weather stations on a thermal image provided by the Advanced Very High Resolution Radiometer (AVHRR) instrument on the *NOAA-11* platform. Bilbao is placed in an area influenced by the Atlantic Ocean, showing an Atlantic climate pattern. Valencia is located at the east coast of the peninsula, capturing the effects of the Mediterranean climate over this zone. Seville, at the south, is placed at a more heterogeneous area influenced by both the Atlantic and the Mediterranean. Madrid is located approximately at the center of the region, capturing the effects of the continental climate. Taking Madrid as reference, the other cities are placed at a distance of 350 (Valencia), 400 (Bilbao), and 540 km (Seville), approximately. Table 2 gives the main statistics of the data at these four stations. The warmer locations are Valencia and Seville, and the cooler ones Madrid and Bilbao. It can also be inferred from the standard deviations that the most variable records are those of Madrid and Seville. These four weather stations capture essentially the main climate trends existing in Spain and are located in very populated cities. To follow the impact of climate on the aggregated electricity consumption, TI is defined as

TABLE 1. Statistics for the calculation of the mean daily temperature. Mean value $\overline{\Delta T}$, std dev $\sigma(\Delta T)$, max ΔT_{max}, and min ΔT_{min} values of the differences between the mean daily temperature calculated as an average of half-hour temperature measurements and as the arithmetic mean of daily max and min temperature values.

	1992	1993	1994	1995	1996	1997	1998	1999	Average
ΔT (°C)	0.0	0.0	−0.1	0.0	0.0	0.0	0.0	−0.1	0.0
$\sigma(\Delta T)$ (°C)	±0.4	±0.4	±0.5	±0.5	±0.4	±0.4	±0.4	±0.5	±0.4
ΔT_{max} (°C)	1.4	1.1	1.3	1.4	1.2	1.8	1.5	1.0	1.3
ΔT_{min} (°C)	−1.2	−1.4	−2.4	−2.5	−1.6	−1.0	−1.9	−1.3	−1.7

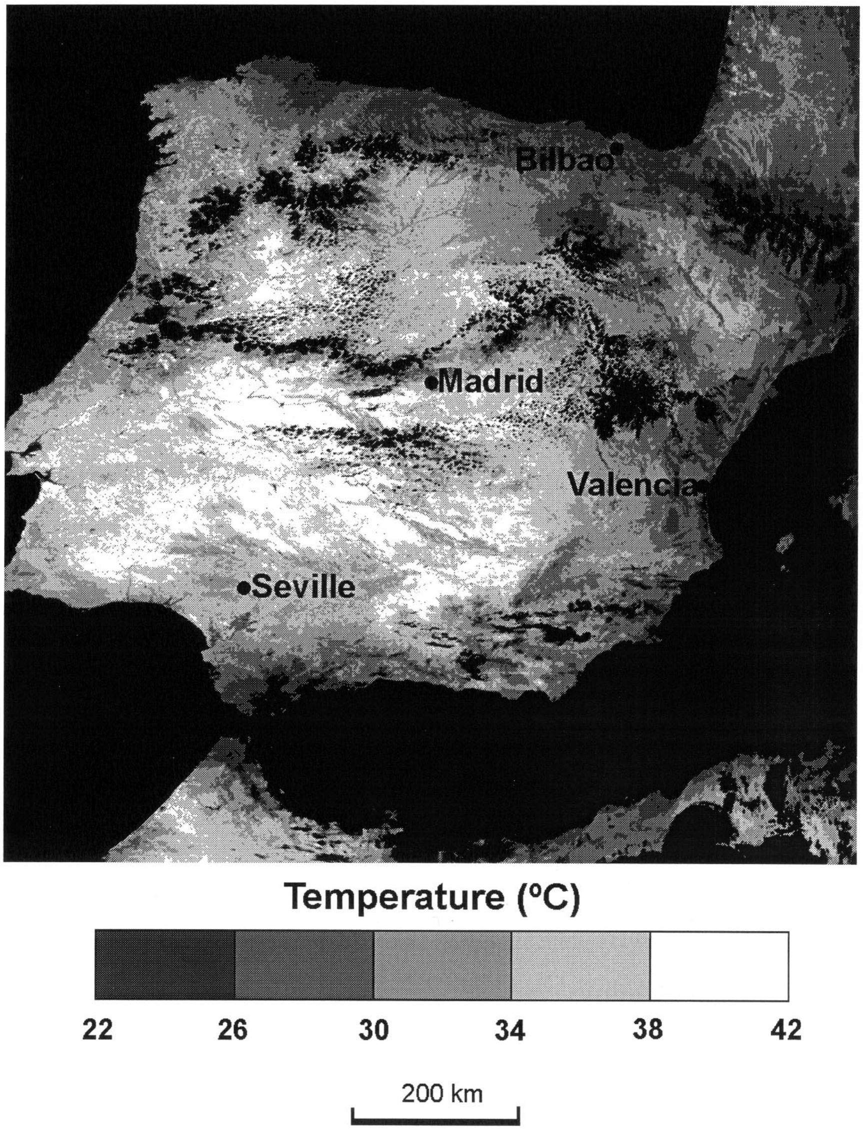

FIG. 4. Temperature image of the Iberian Peninsula recorded by the AVHRR instrument on the *NOAA-11* platform on 26 May 1991, with the locations of the four weather stations indicated. Areas in black denote sea pixels and cloudy pixels.

$$\mathrm{TI}_t = \sum_{i=1}^{4} \overline{T}_{ti} w_{ti}, \tag{3}$$

where $\overline{T}_{ti}$ is the mean daily temperature on day t at weather station i and w_{ti} is a population weight of the area assigned to each station,[1] which is calculated as

$$w_{ti} = \frac{p_{ti}}{\sum_{i=1}^{4} p_{ti}}, \tag{4}$$

with p_{ti} being the total population on day t assigned to weather station i. This approach implicitly assumes equal energy intensity in the four considered regions. This could or could not be the case in Spain, because

TABLE 2. Descriptive statistics of the series of temperature data at the different selected weather stations and for the temperature index TI. The data span the period from 1 Jan 1983 through 30 Apr 1999.

	Mean (°C)	Max (°C)	Min (°C)	Std dev (°C)
Madrid	14.9	32.4	−2.0	7.4
Bilbao	14.6	30.2	−2.2	5.2
Valencia	18.0	33.8	2.0	5.5
Seville	18.9	35.5	2.6	6.5
TI	16.3	30.2	0.6	5.9

[1] For the period considered, the area assigned to Valencia represents about 30% of the population in Spain, Madrid 29%, Seville 22%, and Bilbao 19%, respectively.

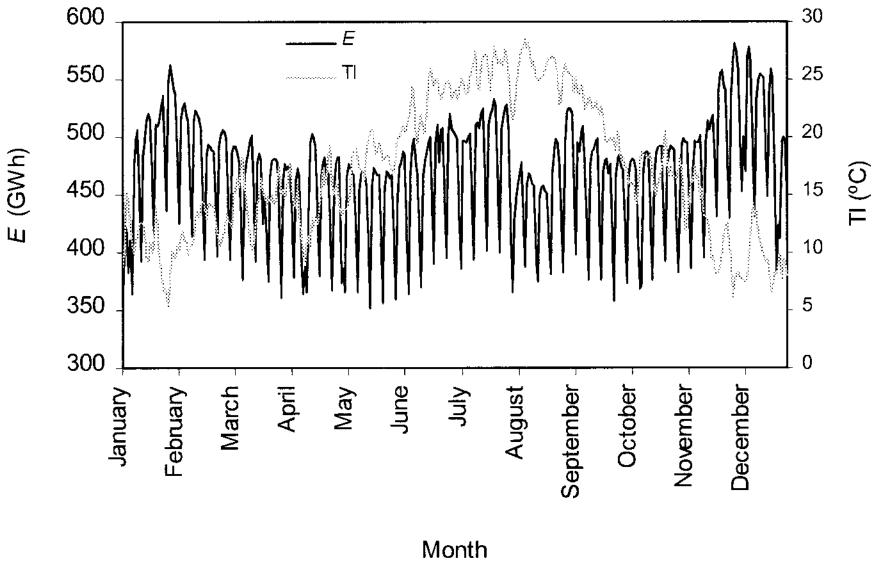

FIG. 5. Evolution of daily *E* and TI in 1998.

the energy consumption depends more on the number of electric heating and air conditioning appliances operating in a given area than on the population. Thus, it would be interesting to make an investigation of the energy intensity of social and economic activities in different areas in Spain (for instance the number of electric appliances in each area) to refine the definition of the index, but this is beyond the scope of the current work.

3. Relationship between electricity load and temperature

Figure 1 presents the evolution of both the monthly *E* and TI. The former shows a significant trend in the long run that is linked to socioeconomic causes, whereas a much softer trend is detected in the latter. The correlation between both variables is apparent: maximum electricity demand values are observed when both maximum (summer) and minimum (winter) temperatures take place. The monthly peak electricity demand in winter is more important than that in summer.

Figure 5 displays the daily evolution in 1998 of *E* and TI. The electricity demand presents a weekly seasonality with minimum values on Sundays (the large falls observed in the curve each seven days) and maximum values on the central working days. This pattern may be disturbed by the existence of single holidays within the week, and also by periods such as Christmas, Easter, or August. By seasons, the electricity load shows maximum values in winter and summer and minimum values in the transition periods, that is, spring and autumn. On the other side, TI presents a daily random fluctuation around its typical monthly trend. This trend is coupled with the one shown by electricity consumption, which shows maximum values coinciding with the TI extreme values (both maximums and minimums). In January, maximum consumption coincides with minimum temperatures. In March–April there is a transition with a near-constant consumption level until May, while temperatures are increasing. Beyond this point, temperature increase causes an electricity load increase in the summer period, except in August. In this month, most people in Spain are on the summer vacation, and this fact could explain the large dip observed in this month, as commented on previously. In September–October, another transition period is observed, with a constant demand level with decreasing temperatures. From November the demand increases together with the temperature decrease, and the cycle is repeated again.

This relationship is better observed in *E* versus TI scatterplots. Figure 6 shows three years selected at the beginning, middle, and end of the sample, respectively. The data have been grouped in two different subsamples that separate the working days on one side from the holidays and weekends on the other side, because the behavior is clearly different. The working-day data show a better correlation with temperature than the holiday data do, due to the greater heterogeneity of the latter.

The relationship is nonlinear, with, roughly speaking, one minimum and two maximums. The minimum value changes slightly from year to year and is located near 18°C. There is an interval centered at this point within which electricity load is insensitive to temperature. Out of this interval, electricity demand jumps with both decreasing temperatures (because of the use of electric heating appliances) and increasing temperatures (because of use of air conditioning). Both in the winter and summer branches of the relationship, there are threshold

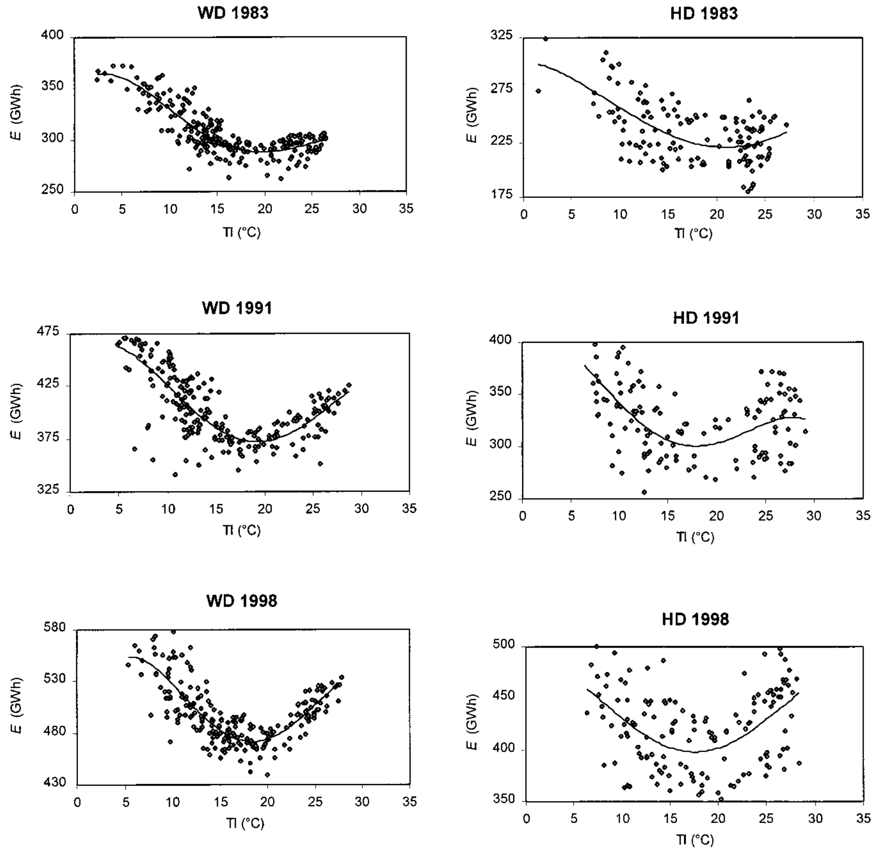

FIG. 6. Scatterplots of *E* vs TI, considering separately working days (WD) and holidays (HD, including weekends), for 1983, 1991, and 1998.

temperatures beyond which the consumption no longer increases (saturation points). This could be due to the limited power of conditioning systems and to the insulating ability of buildings. It would be interesting to correlate those threshold temperatures with the saturation levels of the heating and cooling equipment to find out the level of equipment penetration. This is unfortunately not possible with aggregated electricity data, because they include the effects of very heterogeneous heating and cooling systems. This kind of analysis would be feasible in a much more controlled case, for instance in the analysis of the response of energy consumption to weather conditions at a single building or group of buildings with known characteristics (Eto 1988).

In any given year, the winter branch is more developed than the summer one, indicating a wider response of electricity load to temperature in the cold season. In addition, there has been an increase in the sensitivity over time, which is especially true for summer. Table 3 presents the sensitivity of electricity demand to temperature obtained by linear regression between the two datasets considering only working days and separating the effects in the winter and summer branches. It can be observed that 1) the sensitivity of electricity consumption to temperature in the winter branch increases significantly from 1983 to 1991, and from this year on it remains stable or even decreases slightly in 1998; 2) the sensitivity in the summer branch increases through all the analyzed period, becoming in 1998 almost 5 times larger than it was in 1983; and 3) the sensitivity is always larger for the winter than for the summer case, but the differences decrease over time.

TABLE 3. Sensitivity of the electricity load to the temperature change (MW h °C^{-1}) for the winter and summer branches of the data shown in Fig. 6.

Year	Winter	Summer
1983	−5815	1369
1991	−8000	4071
1998	−7650	6426

4. Heating and cooling demand functions

Because the relationship between electricity demand and air temperature is nonlinear, showing winter and summer branches, it would be convenient to separate these two branches to obtain more straightforward and easily interpretable predictive models (Sailor and Mu-

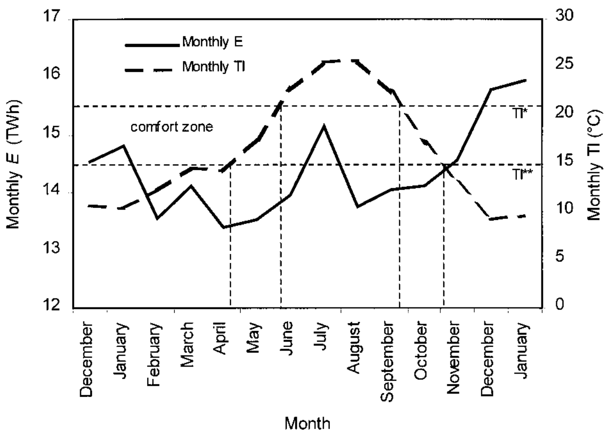

FIG. 7. Evolution of monthly E and TI in 1998, showing the comfort zone.

TABLE 4. Annual HDD and CDD values calculated for the temperature index sample from 1993 to 1998.

Year	HDD (°C)	CDD (°C)
1983	1214	707
1984	1439	545
1985	1333	793
1986	1363	723
1987	1173	738
1988	1154	650
1989	1024	794
1990	1171	834
1991	1420	810
1992	1283	664
1993	1371	628
1994	1084	826
1995	948	787
1996	1165	655
1997	926	778
1998	1099	775
Average	1200	730
Std dev	160	80

ñoz 1997; Lam 1998). This can be accomplished by using the concept of degree-day, which is defined as the difference between the mean daily temperature and a base temperature. This base temperature can be physically interpreted as the outdoor temperature at which solar and internal gains (by electric lighting, equipment, and people) offset heat losses (Eto 1988), and at this point the electricity load becomes insensitive to temperature. Thus, this reference temperature depends on the characteristics of building construction and on the kind of activity developed in a building. As a consequence, different climatic regions and, to a lesser extent, different building types can have different base temperatures.

In our case, the characteristics of the electricity load data do not allow us to determine directly this base temperature, but it can be estimated from the scatterplots of Fig. 6. This base should be the temperature at which the electricity consumption becomes minimum. If this value is selected, then the degree-day variable will take positive values in the summer branch and negative values in winter. Instead of using a unique variable defined in $(-\infty, +\infty)$, it is more common to use two different variables defined in $[0, +\infty)$. This leads to the definition of the cooling degree-day variable CDD = max(TI − TI*;0) and heating degree-day variable HDD = max(TI** − TI;0), where TI* and TI** are the base temperatures for each one, which can generally be different.

Considering the scatterplots shown in Fig. 6, a unique base temperature of 18°C (about 65°F) could be used. This is the standard reference commonly used to calculate heating and cooling degree-days, especially in the analysis of the impact of weather on energy consumption (Le Comte and Warren 1981; Quayle and Diaz 1980; Eto 1988). However, other climatic areas could require other base temperatures, as has been commented on.[2] Another possibility could be to select two different base temperatures for the heating and cooling variables, because there is a nonsensitive temperature interval around 18°C. For instance, the CDD could be defined by taking TI* = 21°C and the HDD by selecting TI** = 15°C. Within these two limits a ''comfort zone'' could be established, in which no heating or cooling is required, as indicated in Fig. 7. In this figure, the two dashed horizontal lines limit two time periods (from April to June of 1998 and from September to November of 1998), when temperature is within TI** = 15°C and TI* = 21°C. The vertical dashed lines indicate the electricity consumption segments within these time periods, which show the minimum sensitivity to temperature in the year. Thus, within the interval 15°–21°C the electricity load is relatively insensitive to temperature, defining the so-called comfort zone.

The HDD and CDD values using a base temperature of 18°C have been calculated for the entire sample. Their annual accumulated values are shown in Table 4, to have some idea of the climatic characteristics and the variations in the degree-day data within the considered period (1983–98). The annual HDD are larger than the annual CDD, indicating that there are more cold days than warm ones. Both series show a similar variability in relative terms (about 12%). A decreasing trend is detected for the HDD and an increasing trend for the CDD, which could be interpreted as a climate warming in Spain during the last 16 yr.

[2] Sailor and Muñoz (1997) used a base temperature of 18.3°C for calculating degree-days in Ohio, Louisiana, and Washington and 21°C for Florida to achieve the best adjustment for the consumption data in each state. Engle et al. (1992) used two different bases (50° and 65°F) to calculate heating degree-days and two others (65° and 70°F) for calculating cooling degree-days. Beenstock et al. (1999) used a base temperature of 10°C for heating degree-days and 25°C for cooling degree-days.

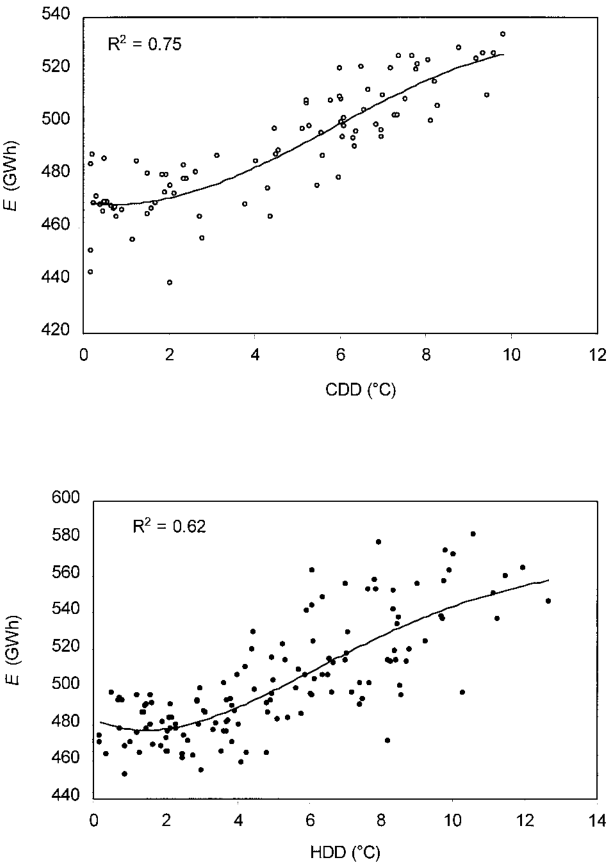

FIG. 8. Daily E in terms of cooling (CDD) and heating (HDD) degree-days in 1998. Only data corresponding to working days are shown.

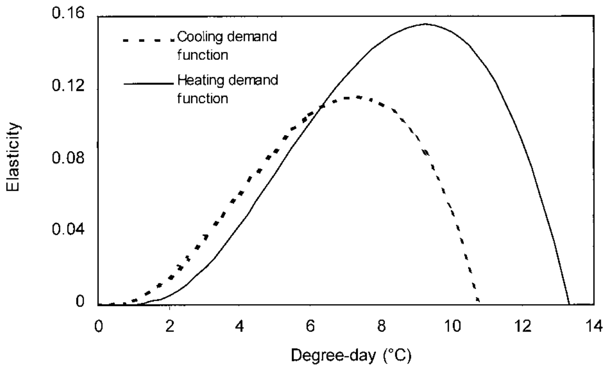

FIG. 9. Elasticity functions calculated for the heating and cooling demand functions in 1998.

Figure 8 shows daily electricity consumption versus daily cooling and heating degree-days calculated by using a base temperature of 18°C for 1998. The two seasonal branches are effectively separated into two functions, namely, the heating demand function $E_{\mathrm{HDD}} = f(\mathrm{HDD})$, and the cooling demand function $E_{\mathrm{CDD}} = g(\mathrm{CDD})$. Each is nonlinear, with an initial insensitivity interval beyond which the demand increases until the saturation points are reached. High determination coefficients are obtained, showing the large explicative power of electricity load by temperature. In addition, the heating demand function predicts electricity consumption with an error of estimate of $\pm 4\%$, and the error for the cooling demand function is $\pm 2\%$ in electricity load. These relationships can be better analyzed by calculating the electricity demand elasticity in both cases, defined as

$$\varepsilon_{\mathrm{HDD}} = \frac{\mathrm{HDD}}{E_{\mathrm{HDD}}} f'(\mathrm{HDD}), \quad \text{and} \tag{5}$$

$$\varepsilon_{\mathrm{CDD}} = \frac{\mathrm{CDD}}{E_{\mathrm{CDD}}} g'(\mathrm{CDD}), \tag{6}$$

where $\varepsilon_{\mathrm{HDD}}$ and $\varepsilon_{\mathrm{CDD}}$ are the elasticities for the heating and cooling demand functions and $f'(\mathrm{HDD})$ and $g'(\mathrm{CDD})$ are the first derivatives of such functions with respect to HDD and CDD, respectively. Elasticity can be used as a measure of the sensitivity of electricity load to temperature changes. Figure 9 presents the elasticity functions for the heating and cooling demand functions in 1998. Both elasticities are negligible until 2–3 degree-days, revealing the comfort zone. The maximum elasticity is observed in 7 CDD and 9 HDD respectively, and, in addition, the maximum elasticity value for the heating function is higher than for the cooling one. The saturation points are reached in 11 CDD and 13 HDD; thus the sensitivity region is larger for the heating function. These characteristics reveal a higher sensitivity of the heating demand function in winter than the one shown by the cooling demand function in summer, as has been commented on previously.

5. Conclusions

In this work, the relationship between electricity load and daily air temperature in Spain has been discussed, through the definition of a population-weighted temperature index based on four weather stations. Electricity demand shows a significant trend related to socioeconomic and demographic factors and also seasonal effects unrelated to weather conditions (weekly and holiday effects), and other factors related to temperature (monthly effects, except August) have been detected. The seasonal variations of electricity demand and temperature are coupled, so demand maximums are observed for both maximum and minimum temperatures within a year.

The observed relationship between both variables is nonlinear, with regions of nonsensitivity (the comfort zone around 18°C and also the region beyond the saturation points) and intervals within which a significant sensitivity of electricity load to temperature is observed. The use of heating and cooling degree-day variables separates the winter and summer branches, allowing a better characterization and quantification of the electricity demand functions. They show significant correlation coefficients and are able to predict electricity consumption with errors of $\pm 2\%$ (cooling demand function) and $\pm 4\%$ (heating demand function).

The analysis has also revealed that the sensitivity of electricity load to daily air temperature has increased along time, in a higher degree for summer than for winter, although sensitivity to HDD is always more significant than sensitivity to CDD. These results have been useful in the derivation of an accurate predictive model for electricity demand in Spain (Pardo et al. 2000, manuscript submitted to *Energy Econ.*).

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