# Modeling the Impact of Temperature on Peak Electricity Demand in California

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**Abstract** This study utilizes historic monthly peak electricity load data of the California Independent System Operator service area and corresponding data of select determinants of peak electricity load (temperature, electricity price and population) to specify a multiple regression model to forecast the impact of temperature on peak electricity demand. The results indicate that the mathematical relationship between temperature and peak electricity demand is in the form of a third-degree polynomial equation whereby peak electricity load increases exponentially with increasing temperature and then approaches constant levels at high (>~90° F) temperatures (signifying that electric systems used for space conditioning are running at maximum capacity). This study attempts to improve upon an existing forecasting model indicating a quadratic relationship between temperature and peak electricity demand whereby peak electricity load increases exponentially with increasing temperature.

## Introduction

The issue of global warming, the observed increase in globally averaged temperatures and its projected continuation, is perhaps one of the most serious challenges posed to today's scientific and political communities. In 1976, the World Meteorological Organization (WMO) issued the first authoritative statement on the accumulation of carbon dioxide in the atmosphere and the potential impacts on climate and recognized this phenomenon as one of the most serious problems facing global sustainable development (WMO, 2007). The WMO and the United Nations Environment Programme (UNEP) established the Intergovernmental Panel on Climate Change (IPCC) in 1988 to assess scientific information on climate change, its potential impacts and options for adaptation and mitigation (IPCC, 2001). As of June 2007, one hundred seventy-five countries have ratified the Kyoto Protocol, an agreement made under the United Nations Framework Convention on Climate Change, committing to reduce their emissions of carbon dioxide and five other greenhouse gasses or engage in emissions trading (Quarles, 2007). Additionally, the 2007 Nobel Peace Prize was awarded to the IPCC and Albert Gore for their contributions to and efforts in the area of climate change science and advocacy (Nobelprize.org).

The marked importance of climate change by the scientific community has spurred the need for research in areas of mitigation, impacts, and adaptation. Current research on climate change denotes two areas of greatest concern: the impacts of climate change on the physical environment and the socio-economic impacts of climate change (Baxter & Calandri, 1992). Research on how climate change impacts the physical environment include studies on climate-sensitive ecosystems, changes in glacier melting, sea level rise, sea-surface temperature and ocean acidity, impacts on precipitation, aridity and extreme weather events, and impacts on biological diversity (Baxter & Calandri, 1992). Research on socio-economic impacts of climate change includes studies on changes in water resources, air quality, health and disease vectors, shifting agriculture and its implications on food resources and impacts of climate on energy use (Baxter & Calandri, 1992).

Energy use and climate change is perhaps one of the most intriguing areas of emphasis because climate change affects both energy demand and supply. Hydroelectric power will most likely be the most impacted of all energy sources because it is dependent on both timing and quantities of precipitation, snow melt and stream flows, all of which will be impacted by climate change. It is anticipated that hydroelectric power generation will be diminished or destabilized as a result of climate change (IPCC, 2001). It is estimated that a slight decrease in precipitation could decrease California's hydroelectric power supply by ten to thirty percent by the end of this century (Miller, et al., 2007). Climate change will also impact and potentially diminish other energy sources such as solar energy, due to increased cloud cover; wind production, due to diminished wind speeds; and production of biomass, due to changes in growing seasons (IPCC, 2001). On the demand side, climate change and the corresponding increase in global average temperatures and significant increases in frequency, intensity and duration of summertime extreme heat days will most likely lead to a significant increase in energy demand due to the need for indoor air conditioning (Miller & Hayhoe, 2006). The IPCC uses estimates from six Special Report on Emissions Scenarios (SRES) to project a very likely (>90% probability) increase in warm spells and heat wave frequency over most land areas in the twenty-first century (IPCC, 2007). Continuous demand during hot summers can overload existing electric systems, damage power lines, transformers, and electrical equipment and result in power outages.

California, one of the world's largest economies, is a major area of concern regarding energy demand. Although California's per capita electricity demand has remained steady since 1973 due to energy efficient programs, the increased growth in population and technology in conjunction with the anticipated increase in air conditioning use shows an upward trend in aggregate peak electricity demand approaching 67 Gigawatts in 2016, representing a 14% increase in one decade (CEC, 2005). California currently experiences electric supply reliability problems as demand frequently exceeds the available generating and/or transmitting capacity. This problem has contributed to the problem of industries moving out of California as some industries relocate to regions where electricity supply is more dependable (CEC, 2005).

The California power grid is a network of over twenty-seven thousand miles of high-voltage power lines connecting 979 power plants, almost fifty private and publicly owned utilities, and over thirty million customers (CAISO, 2007). Over 200,000 Giga-watt hours of power are delivered annually through this network (CAISO, 2007). To ensure that electricity generation supply meets demand and that electricity is adequately delivered, the California Independent System Operator (CAISO), an independent third party organization was formed at the direction of the Federal Energy Regulatory Commission (FERC) to act as the intermediary between power plants and utilities, and to manage, control and monitor the operations of this vital and complex power grid (CAISO, 2007).

CAISO utilizes various models to forecast two-day-ahead, one-day-ahead, and hourly electricity demand to determine what the load (total electricity demand) will be for each hour of the day (CAISO, 2007). Perhaps the most critical feature of the load forecast is the peak load. The peak load is the maximum requirements of the network at a given time, when the electricity need is the greatest. Usually, the peak load occurs between the hours of two and four o'clock in the afternoon with even greater peaking in the summer due to air conditioning use. When electricity usage nears the peak load, the grid is operating to near capacity, "peaker plants" (usually less efficient, more polluting plants) are called into operation, electricity prices are the highest, and there is increased risk of system failure and power outages (CAISO, 2007).

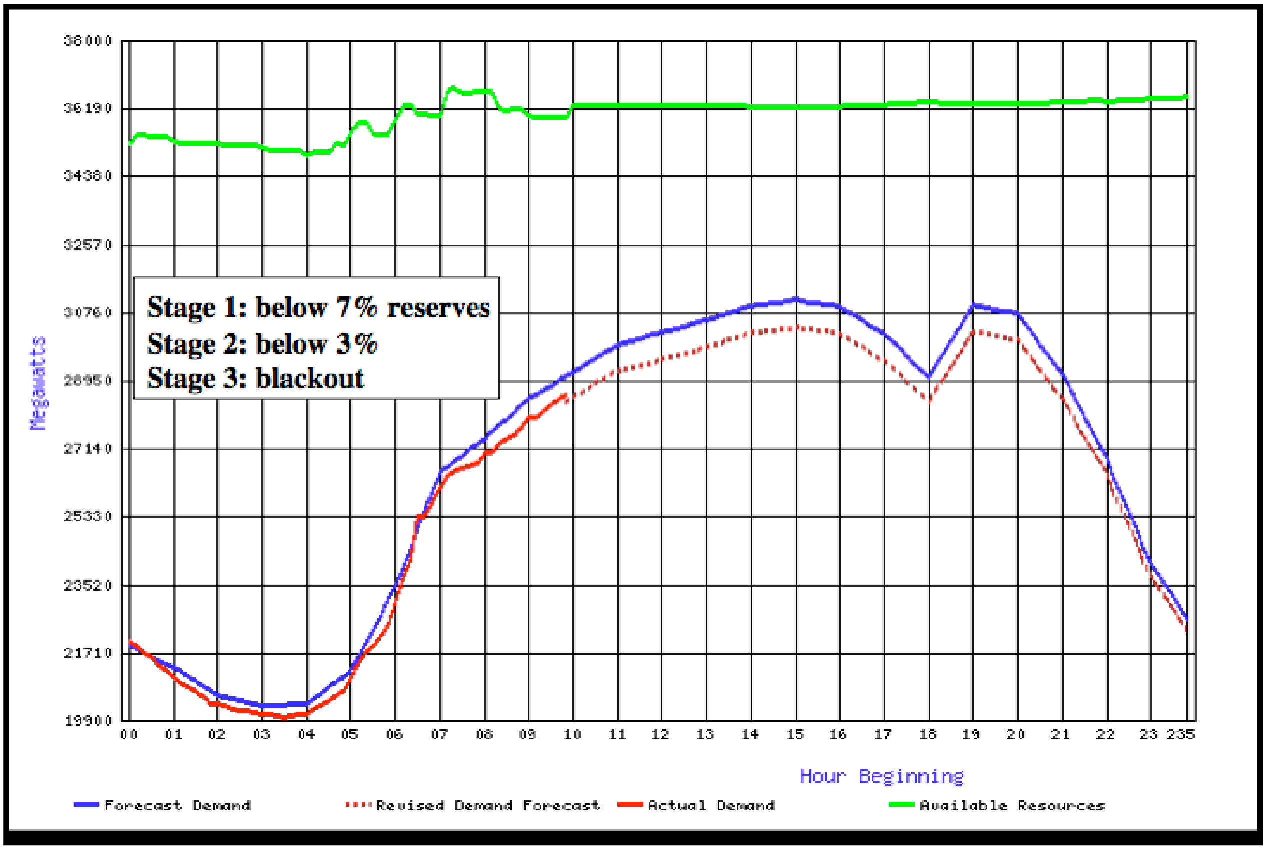

**Figure 1: CAISO Peak Load Graph (shows peak load fluctuations for a 24-hour period)**
**Emergency Stage 1 (grid operating below 7% reserves)**
**Emergency Stage 2 (grid operating below 3% reserves)**
**Emergency Stage 3 (no reserves – blackouts necessary)**

Many studies have researched electricity demand as a function of temperature. Baxter & Calandri (1992) assessed electricity needs in California resulting from temperature change. Historical data is observed and superimposed in a highly theoretical operations model to project electricity demand for a fixed date in the future. Rosenthal, et al. (1995) quantifies the relationship between global warming and U.S. energy expenditures for space heating and cooling in residential and commercial buildings. In their analysis, the total increase in energy use is derived and an econometric model is developed. However, the study does not address peak electricity demand or load. Hor, et al. (2005) developed a multiple regression model to forecast monthly electricity demand in the U.K. In this study, a correlation is established between electricity demand and weather-related parameters. Although peak load is not addressed in this study, the regression model is relevant and statistically significant.

Perhaps the most intriguing matter and the impetus for my study is the outcome of the regression model utilized by CAISO (2007) in their peak load forecasting. The relationship between peak load and temperature in the regression model used by the California Independent System Operator (CAISO) is in the form of a second-degree polynomial (quadratic equation) where peak load approaches infinity at high temperatures (CAISO, 2007) (Fig. 2). The a priori expectation of this study is that when all systems requiring electricity are in use (i.e. at high temperatures, most people are using air conditioning), if temperatures were to increase, the increased electric load would not continue to increase exponentially, but approach constant levels when electric systems are already running at maximum capacity (assuming no unusual additions to the electric systems, i.e. mass purchase and use of room air conditioning units on very hot days). Thus, this study hypothesizes that the relationship between peak load and temperature is better represented in the form of a third-degree polynomial rather than a second-degree polynomial.

The second-degree polynomial (quadratic equation) possesses the general functional form of: $y = a + bx + x^2$. The third-degree polynomial possesses the following general functional form: $y = a + bx + bx^2 + bx^3$. The visual difference in these two functional forms is shown in Figure 3 with the hypothesized model (third-degree polynomial) superimposed on the CAISO model (second-degree polynomial). The CAISO model (by applying a quadratic functional form) projects peak electricity load approaching infinity as temperature rises. By specifying a third-degree polynomial, the hypothesized model projects a leveling out of peak electricity load as temperatures rise above approximately 90° F.

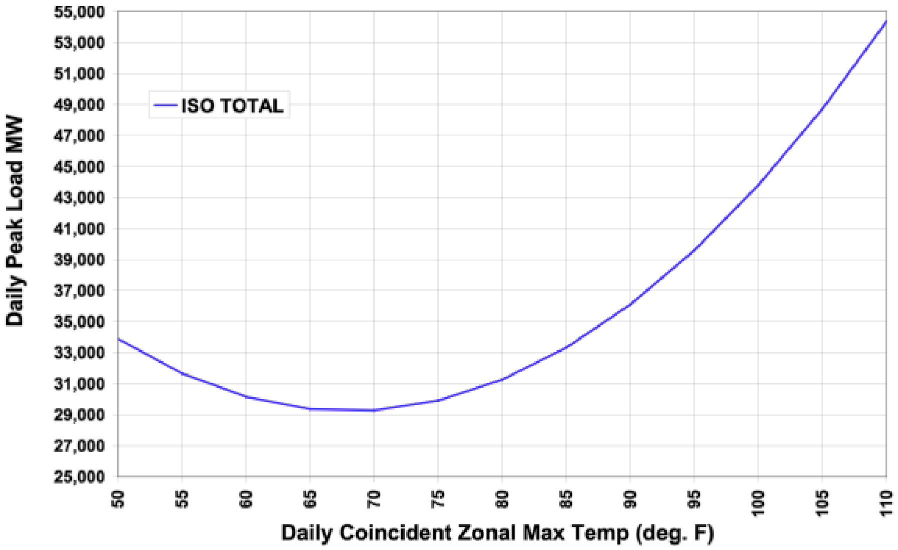

**Figure 2: CAISO Daily Peak Load Forecast generated with Itron's MetrixND Energy Forecasting Software (Second Degree Polynomial (Quadratic) Relationship Between Temperature and Peak Load)**

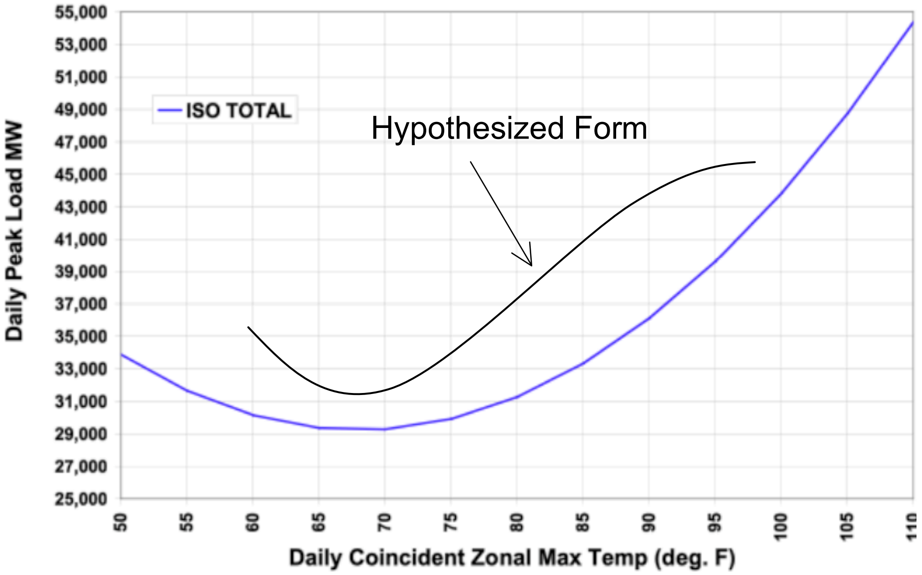

**Figure 3: Hypothesized Model of Peak Load and Temperature (third-degree polynomial relationship) superimposed on CAISO peak load forecast (quadratic relationship)**

This study aims to improve upon existing methods of forecasting and quantifying future electricity needs due to increasing temperature. It is a step towards gaining understanding of climate change impacts and adaptation. Improved models, such as this study aims to achieve, can aid in future energy resource planning, energy conservation efforts, load-shifting, and other areas of energy systems operations management. Improved electricity load forecasting could possibly reduce the instances of costly power outages, the need for bringing inefficient, polluting "peaker" plants on line, and generally improve the dependability and market efficiency of the California power grid.

## Methods

Data of historical peak loads and determinants of electricity demand (population data, temperature data and electricity price data) were used to create a regression model of peak load as a function of temperature, which fits the hypothesized expectation that peak load and temperature have a relationship that fits a third-degree polynomial (Fig. 3)

**Data** Electricity prices were attained via the consumer price index for electricity using Bureau of Labor Statistics data. California population data were attained from the U.S. Bureau of the Census (U.S. Census Bureau, 2007), California high temperatures were attained for eleven weather stations (Ukiah, Sacramento, Fresno, San Jose, San Francisco, Long Beach, Burbank, Riverside, Lindbergh Field, Miramar and El Cajon) within the four major planning areas of the California Energy Commission (Pacific Gas & Electric, Southern California Edison, San Diego Gas & Electric, and Los Angeles Department of Water and Power), (Western Regional Climate Center, 2007). Because residential air conditioning is the primary driver of day-to-day changes in peak demand (CEC, 2007), weather station data was weighted based on the estimated number of residential air conditioning units in each of the utility forecast zones assumed in the California Energy Commission's residential demand forecast model (CEC, 2007). CAISO peak load data was attained from CAISO Federal Energy Regulatory Commission form 714 filings (CAISO, 2007). All data were monthly figures from January 1993 to December 2003.

**Model Development** A statistical model was developed utilizing a priori expected relationships between electricity demand and its determinants (population, price of electricity and temperature):

$$\mathbf{y} = \boldsymbol{\beta}_\circ + \boldsymbol{\beta}_1\mathbf{x}_1 + \boldsymbol{\beta}_2\,(\mathbf{1/x}_2) + \boldsymbol{\beta}_3\mathbf{x}_3 + \boldsymbol{\beta}_4\mathbf{x}_3^2 + \boldsymbol{\beta}_5\mathbf{x}_3^3 + \boldsymbol{\varepsilon}$$

where y is the total peak electric load in the CAISO service area for the hour and day of the month with the highest usage. $x_1$ is the California population; $x_2$ is the price of electricity; and $x_3$ is the daily maximum representative temperature in California. As can be observed in the model's specification, temperature is expressed as a third-degree polynomial. The third degree polynomial is specified because it provides a measure of the relationship between peak load and temperature, which is expected to conform to the observed data. $\beta_\circ$ provides a measurement of the impact of variables not included in the equation (determinants of peak load other than temperature, population and electricity price). Mathematically, $\beta_\circ$ is the y-axis intercept of the linear function. $\beta_1$ shows the change in peak load (megawatt hours) per unit change (# people) in the California population. $\beta_2$ shows the change in peak load (megawatt hours) per unit change in the inverse of electricity price (1 / consumer price index for electricity use). $\beta_3$ shows the change in peak load (megawatt hours) per unit change in temperature (degrees Farenheight). $\beta_4$ shows the change in peak load (megawatt hours) per unit change in temperature (degrees Farenheight) to the second power and $\beta_5$ shows the change in peak load (megawatt hours) per unit change in temperature (degrees Farenheight) to the third power. When specifying the model in this structural form, $\beta_3$, $\beta_4$ and $\beta_5$ should be observed as a group (the results of these individual values independently do not have meaning). Their group meaning is shown in the line (hypothesized model) in Figure 3. Figure 3 shows the combined effect of $\beta_3$, $\beta_4$ and $\beta_5$ while $x_1$ and $x_2$ are held constant (at the value of final data point of each variable).

The CAISO model was not specified in this study. It is generated by a proprietary software (Itron MetrixND Energy Forecasting Software) whose programming specification and statistical results are not available to the public. The only statistical information revealed in the CAISO model is that the relationship between peak load and temperature was specified as a quadratic equation. This was shown graphically. The other variables in the CAISO model was simply stated as economic and population data (CAISO, 2005).

**Multiple Regression Analysis** Historical data were plotted on a graph with temperature and peak load as the x and y-axes respectively (Fig. 4). Multiple regression analyses were run on the historical data transforming temperature values to the third degree (hypothesized third-degree polynomial relationship), second degree (estimated CAISO quadratic relationship) and lastly using non-transformed temperature values (linear relationship) to determine the $\beta_i$ coefficients and the resulting models were determined:

Third-degree polynomial relationship:

$$\mathbf{y = 549{,}391 + .00170(x_1) + 1{,}030{,}481(1/x_2) - 23{,}131(x_3) + 296.48(x_3)^2 - 1.2309(x_3)^3}$$

Estimated CAISO quadratic relationship:

$$\mathbf{y = 30{,}921 + .00169(x_1) + 961{,}808(1/x_2) - 2{,}159(x_3) + 16.9567(x_3)^2}$$

Linear relationship:

$$\mathbf{y = -63{,}755 + .00165(x_1) + 965{,}070(1/x_2) - 409(x_3)}$$

Regression statistics were evaluated to determine the statistical significance of the models and the accuracy of their respective regression coefficients.

## Results

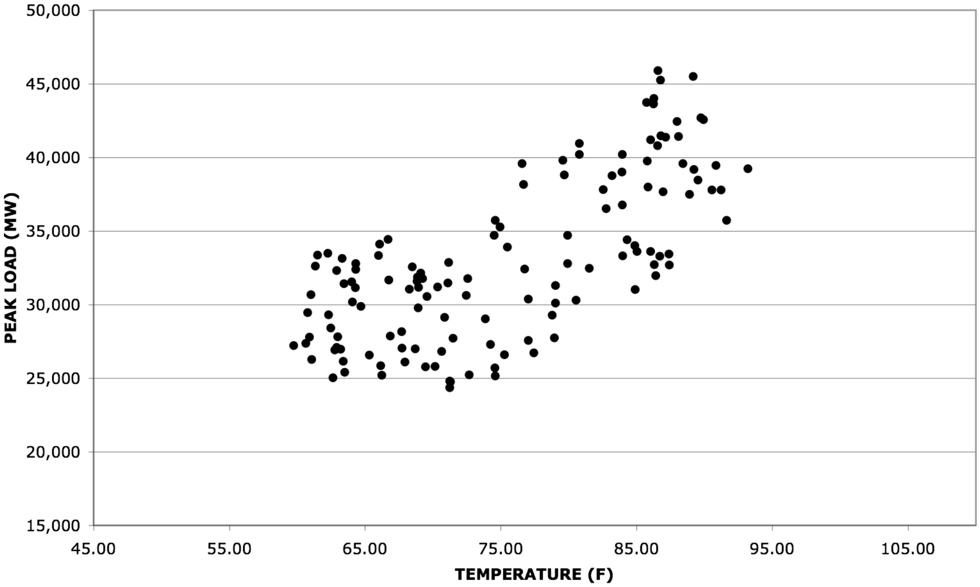

Figure 4. Historical Monthly Peak Loads of CAISO Service Area (1993 – 2003) and corresponding temperatures. Temperature data from 11 weather stations were weighted to obtain representative temperatures of the state of California.

The hypothesized model (the third-degree polynomial relationship) explains 84% of the variation in peak electricity demand ($R^2 = 0.84$). Of further statistical importance, the absolute value of the t-statistic corresponding to every regression coefficient for the hypothesized model is greater than 3.99 and possesses the correct theoretical sign, indicating statistical significance for each regression coefficient. The t and p-values are shown in Table 1.

Table 1. Regression Statistics Comparing $2^{nd}$ Degree and $3^{rd}$ Degree Temperature and Peak Load Relationships

| | Temperature & Peak Load Relationship | | |
|---|---|---|---|
| | 3rd Degree (Hypothesized) | 2nd Degree (Quadratic) | 1st Degree (Linear) |
| Adjusted $R^2$ | 0.838205 | 0.819100 | 0.767451 |
| Standard Error | 2207 | 2334 | 2646 |
| *t Statistics* | | | |
| Intercept | 4.20811 | 1.889962 | -10.452966 |
| Variable 1 (Population) | 14.55728 | 13.644964 | 11.815372 |
| Variable 2 (Electricity Price) | 4.18958 | 3.707191 | 3.280782 |
| Variable 3 (Temperature) | -4.398616 | -5.143539 | 16.922773 |
| Variable 4 ($Temperature^2$) | 4.239098 | 6.127502 | |
| Variable 5 ($Temperature^3$) | -3.999454 | | |
| P-Values | | | |
| Intercept | 4.85353 E-05 | 0.061042299 | 7.22063 E-19 |
| Variable 1 (Population) | 9.09389 E-29 | 1.16954 E-26 | 3.07459 E-22 |
| Variable 2 (Electricity Price) | 5.21442 E-05 | 0.000311747 | 0.001334037 |
| Variable 3 (Temperature) | 2.29375 E-05 | 9.94439 E-07 | 1.8799 E-34 |
| Variable 4 ($Temperature^2$) | 4.30289 E-05 | 1.03885 E-08 | |
| Variable 5 ($Temperature^3$) | 0.000107524 | | |

The third-degree regression statistics are stronger than the regression statistics corresponding to the quadratic relationship between temperature and peak load. The $R^2$ (the percentage of variation on the peak load usage that is explained by the estimated regression equation) of the quadratic is lower - - 82%, as compared to 84% in the third-degree equation. The t statistics in the third-degree equation are statistically significant at the 5% level of significance for every regression coefficient. In the quadratic, the intercept is not statistically significant; the t statistic is 1.89 and the corresponding p-value is .06, which is greater than the critical p-value of .025.

**F-test** To further confirm the hypothesis that the third-degree equation statistically outperforms the quadratic equation, an F-test was conducted to ascertain statistically if the addition of variable 5 ($Temperature^3$) results in an improved specification of the model:

$$\mathbf{F = \frac{(R^2_{\text{with variable 5}} - R^2_{\text{without variable 5}}) / k_{\text{with variable 5}}}{(1-R^2_{\text{with variable 5}}) / n - k_{\text{with variable 5}}}}$$

$H_o$: Addition of variable 5 (Temperature$^3$) does not improve model

$H_A$: Addition of variable 5 (Temperature$^3$) improves the model

If $F > F_{\text{critical table value}}$, reject null hypothesis

$F = 8.4151$

$F_{\text{critical table value}} = 3.92$ at the 5% level of significance

$F > F_{\text{critical table value}}$, therefore, the null hypothesis can be rejected and specifying temperature to the third-degree is an improvement to the existing CAISO model which specifies that temperature has a second-degree relationship with peak load.

The results of the F test are robust. For sample sizes greater than 30, the Central Limit Theorem will hold (Research & Education Association, 2000). The sample size in this study equals 132 observations. Even if the distribution of $y_i$ is unknown, a Central Limit Theorem permits us to state that the least squares estimator will be approximately normally distributed for sample sizes usually employed in practice (Griffiths, et al., 1993). But even without assuming the $y_i$ are normal, as sample size increases, the distribution of $\beta$ will usually approach normality; this can be justified by a generalized form of the Central Limit Theorem (Wonnacott & Wonnacott, 1970). Griffith asserts that the normality assumption permitted us to use the t- and F-statistics for testing linear hypotheses about the coefficient vector $\beta$ (Griffiths, et al., 1993).

**t-test of Statistical Significance** Additional evidence that the third-degree coefficient improves the model comes from the fact that the t-statistic associated with temperature$^3$ is 3.99 and the associated p-value is .0001, which establishes that a statistically significant relationship exists between peak load and temperature$^3$.

**Graphing Functional Form** To isolate the effect of temperature on peak load, population and electricity price were held constant. Population and electricity price data from the last year of the data set were substituted for variables $x_1$ and $x_2$ respectively to graph the functional form of the temperature/peak load relationship (Fig. 5) resulting in the following equation:

$$\mathbf{y = 622{,}086 - 23{,}131 * (\text{Temperature}) + 296.48 * (\text{Temperature}^2) - 1.2309 * (\text{Temperature}^3).}$$

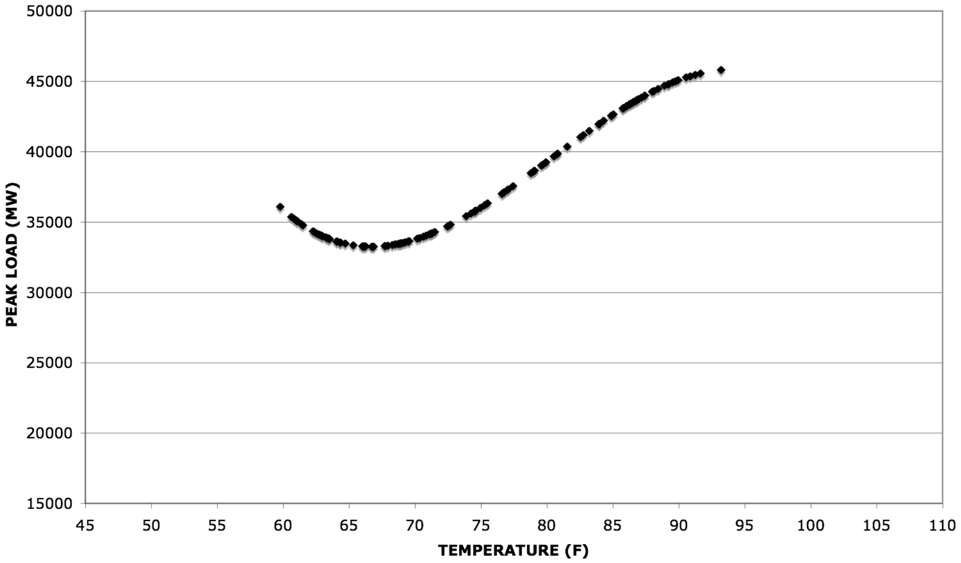

Figure 5. Peak Load Model. Model-derived relationship of Peak Load and Temperature. Population and electricity price held constant to isolate effect of temperature on peak load.

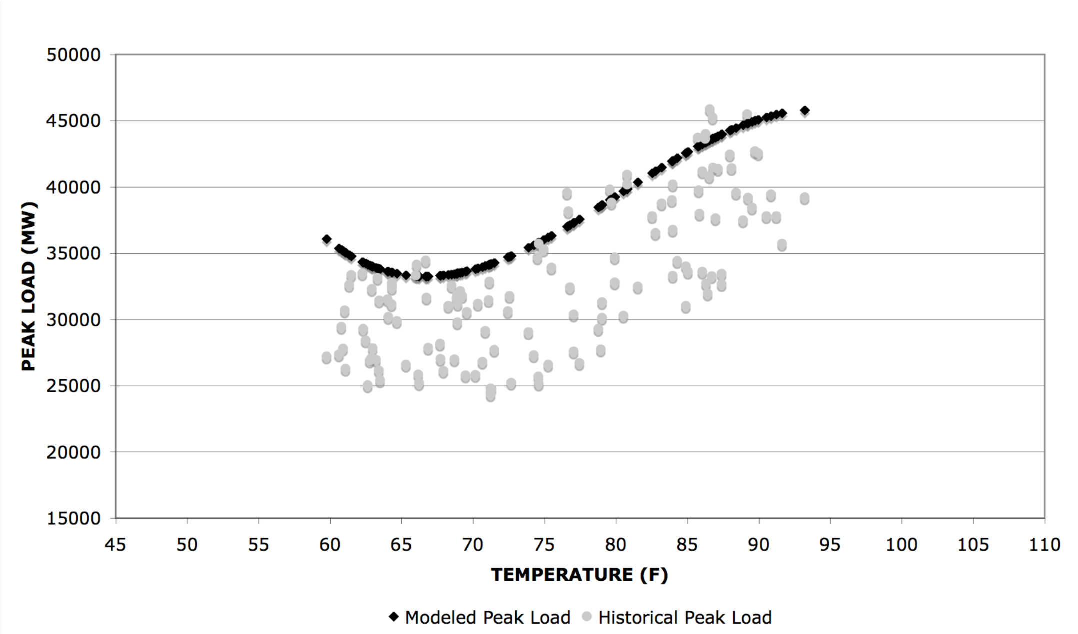

Figure 6. Historical Peak Load & Modeled Peak Load. Model-derived relationship of peak load and temperature superimposed over historical peak load data

**Application** Population and electricity price data from the last year of the data set were substituted for variables $x_1$ and $x_2$ respectively to calculate peak load at various temperature scenarios and compare resulting peak load values from the CAISO quadratic equation and the third-degree polynomial equation (Table 2):

quadratic equation:

$$\mathbf{y = 30{,}921 + .00169(x_1) + 961{,}808(1/x_2) - 2{,}159(x_3) + 16.9567(x_3)^2}$$

third-degree polynomial equation:

$$\mathbf{y = 622{,}086 - 23{,}131 * (Temperature) + 296.48 * (Temperature^2) -1.2309 * (Temperature^3)}$$

The model-derived values for the points on Figure 5 are shown in Table 2. The actual (historic) values are shown in Figure 4. As can be observed in Table 2, for temperatures between temperatures of 75 and 89 degrees Farenheight, there is not much difference in peak load figures generated by the quadratic and third-degree models. However, as temperatures exceed approximately 90 degrees Farenheight, the peak loads generated by the two models differ significantly. At very high temperatures, the difference in peak load is dramatic and would imply a very different implementation of resources and level of operations for the grid.

Table 2. Peak Load Values at Various Temperatures. Comparison of Quadratic and 3rd Degree Models

| **Temperature** **(F)** | **Peak Load (MW)** Quadratic Relationship **(a)** | **Peak Load (MW)** 3rd Degree Relationship **(b)** | **Difference in Peak Load (MW)** **(a-b)** |
|---|---|---|---|
| 75 | 35,928 | 35,657 | 271 |
| 76 | 36,330 | 36,245 | 85 |
| 77 | 36,765 | 36,864 | (99) |
| 78 | 37,235 | 37,508 | (274) |
| 79 | 37,738 | 38,169 | (431) |
| 80 | 38,275 | 38,839 | (564) |
| 81 | 38,846 | 39,512 | (666) |
| 82 | 39,451 | 40,179 | (728) |
| 83 | 40,090 | 40,833 | (743) |
| 84 | 40,762 | 41,468 | (705) |
| 85 | 41,469 | 42,075 | (605) |
| 86 | 42,210 | 42,647 | (437) |
| 87 | 42,984 | 43,177 | (193) |
| 88 | 43,793 | 43,657 | 135 |
| 89 | 44,635 | 44,081 | 554 |
| 90 | 45,511 | 44,440 | 1,071 |
| 91 | 46,421 | 44,727 | 1,694 |
| 92 | 47,366 | 44,936 | 2,430 |
| 93 | 48,343 | 45,057 | 3,286 |
| 94 | 49,355 | 45,085 | 4,270 |
| 95 | 50,401 | 45,012 | 5,389 |
| 96 | 51,481 | 44,830 | 6,651 |
| 97 | 52,595 | 44,532 | 8,062 |
| 98 | 53,742 | 44,111 | 9,631 |
| 99 | 54,924 | 43,558 | 11,365 |
| 100 | 56,139 | 42,868 | 13,271 |
| 101 | 57,388 | 42,032 | 15,356 |
| 102 | 58,672 | 41,043 | 17,629 |
| 103 | 59,989 | 39,894 | 20,095 |
| 104 | 61,340 | 38,577 | 22,763 |
| 105 | 62,725 | 37,084 | 25,640 |

## Discussion

This study identified that peak electricity usage due to increasing temperatures is in line with a third-degree polynomial function, thus, at very high temperatures, peak electricity usage will not increase exponentially but will level out as all air conditioning systems are theoretically on and are running at peak capacity. As seen in Table 2, for temperatures below 90°F, use of either the quadratic model or the third-degree model does not show a significant impact on calculating peak load. However, at high temperatures, there is a significant difference in peak load. For example, at 100°F there is a 13,271 difference in peak load values. This difference in forecast could translate into money, resource and pollution saving potential as foreknowledge of reduced peak load can plan for better operation of the electrical grid by utilizing cleaner, more energy efficient plants. Furthermore, accurate peak load forecasting is important in climate impact research to ensure there is sufficient infrastructure and capacity to meet the load requirements of the California grid.

This study did not address changes in technological development. It is possible that global warming may create a move toward reengineering or retrofitting electrical systems (particularly air conditioning systems and insulation systems) to make them more energy efficient. A significant change in technology may diminish the high temperature peak electricity use or diminish peak electricity use at all temperature points. On the other hand, in the short term, an abrupt change in climate (sudden warming scenario) without significant technological development may affect immediate appliance purchase decisions. People who previously did not need space cooling equipment are likely to adapt to warming by purchasing such equipment, thus significantly adding to the electrical load (Baxter & Calandri, 1992).

This study examined the impact of increasing temperatures on peak demand electricity usage for California. This state should be of particular interest to climate impact researchers due to the region's topographic, climatic and economic diversity. Within it lie the highest and lowest geographical points in the continental United States. (Baxter & Calandri, 1992). The varied regional climates include coastal areas, desert regions, wet northern regions, hot interior valleys and cooler mountain areas. California's economy is immense and diversified as it includes major manufacturing services, is one of the largest areas of agricultural production, and is rapidly growing in service and technology sectors.

This study aimed to improve upon existing methods of forecasting and quantifying future electricity needs due to increasing temperature. It is a step towards gaining understanding of climate change impacts and adaptation. Improved models, such as the one developed for this study, can aid in future energy resource planning, energy conservation efforts, load-shifting, and other areas of energy systems operations management. Improved electricity load forecasting could possibly reduce the instances of costly power outages, the need for bringing inefficient, polluting "peaker" plants on line, and generally improve the dependability and market efficiency of the California power grid.

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