ON THE TEMPERATURE DEPENDENCE OF THE LOAD CURVE OF THE CITY OF ZURICH

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ABSTRACT

This paper deals with the correlation between electricity consumption in the City of Zurich and outside temperature. The motivation is the significant increase of peak load during the summer months since the record summer of 2003.

It can be expected that periods of high temperatures will become more frequent in the future. Furthermore a trend to rising energy consumption in summer can be observed. Therefore it is important for energy suppliers as well as distribution grid operators to analyze how and to what extent these high temperatures are affecting consumer behaviour. This contribution also gives valuable indications regarding:

- *Evolution of peak load in the future*
- *Dimensioning of the distribution grid*

INTRODUCTION

The city of Zurich has an electric energy consumption, which grew annually since 2000 by about 1.2% to approximately 3,060 GWh in 2010 [1] where it is currently stagnating, as Figure 1 shows.

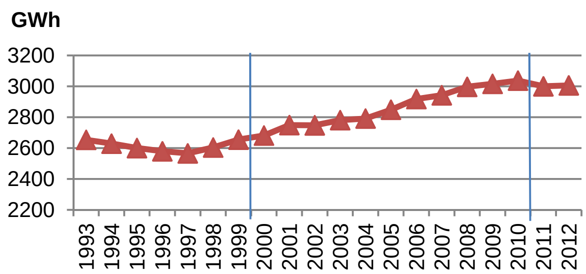

Figure 1: Annual energy consumption of the city of Zurich from 1993 to 2012 in GWh

In the period from 1998 to 2009, the consumption during the summer months (April to September) approached the consumption in the winter season (October to March).

The same observation is made for summer peak load, which came closer in this period to the peak load (real part) in the wintertime. However this trend was less consistent.

For network operation this is a desirable effect in principle, because it results in a more uniform utilization of the power supply system.

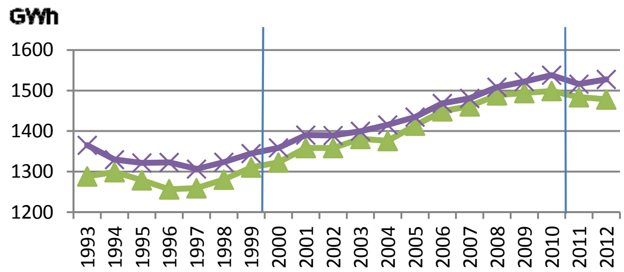

Figure 2: Energy consumption for both summer and winter months from 1993 to 2012 in GWh

This convergence between summer and winter energy consumption as well as peak load was observed for the first time in 2003 and again, clearly amplified, in 2006, both were years with very warm summer months.

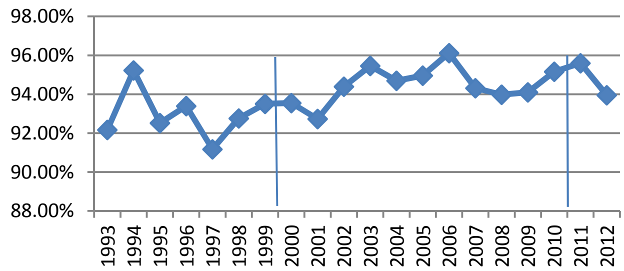

Figure 3: Ratio summer maximum / winter maximum in%

As shown in this study, a certain proportion of the general load increase can be explained by an increase in temperature-sensitive loads such as large and small air-conditioning systems.

Various aspects of temperature dependence of the electrical energy consumption are described by regression techniques [2,3] in the following sections. The key findings are:

- The temperature dependence follows a polynomial trend of fourth degree, minimum value of the trend between 13°C and 16°C (= no demand for heating or cooling energy).
- A linear to slightly quadratic increase of the load in the negative temperature direction between -10°C and 10°C (around 1 to 2 MW for a decrease of 1°C).
- A strong increase at temperatures above 20°C (4-10 MW/°C).
- A saturation effect for temperatures above 30°C. However, this effect was observed in this temperature range only in the years before 2007.

The following data were used for the study:

- The real power sum of all loads of the city of Zurich, in the form of half-hourly mean values of the years 2000 to 2010 (original values are 15min mean values).
- The temperature data as 1/2h-mean values (original values are 10min-mean values) from a monitoring station of the Swiss Metrology Institute in the city of Zurich.
- Radiation data from two weather stations in the city, also in the form of 1/2h-mean values of global radiation (original values are 10min-mean values).

BUILDING A REGRESSION MODEL

First hypotheses were examined in a preliminary analysis [2] on parts of the data set to find the optimal modeling of the various effects of temperature on the load profile.
Beside simpler facts, that the load profile has a seasonal pattern, which is influenced by holiday periods (e.g. summer - and Christmas holidays) or a daily pattern, which is different for workdays and weekends, one has to consider following, less straightforward factors affecting temperature dependency of the load.

Influence of temperature on the load

The daily variation of the load curve is strongly correlated with the outside temperature (minimum at night, maximum during day). However, the outside temperature is only one factor influencing the load curve.
The temperature-dependent part is explained by the heating capacity at lower temperatures and the cooling capacity at higher temperatures.
The daily cycle of the cooling power clearly corresponds to the temperature (maximum during the day and minimum at night). However, applied to the heating power it is not simply reverse. During the night heating is often reduced, therefore also on cold days a maximum during the day for the heating power can be expected.

Influence of radiation on the load

Since the sunlight, which we will refer to as brightness, affects the demand for light as well as the outside temperature, brightness has to be considered in this model. A good parameter is the global irradiance on a horizontal surface, I_G [Wm^{-2}].

The temperature-independent part of the daily load curve comprises inter alia electricity consumption for lighting and depends therefore on brightness. The latter is in turn strongly positively correlated with the temperature. By not controlling for brightness the influence of the temperature would be overestimated.

The pre-analysis showed that the radiation effect (global radiation) on the load can be modeled with a simple linear relationship.

Regression model

From the preliminary study [4] a regression model emerged, which is formulated in such a way that the load P can follow, according to the season and according to the type of day, weekday or weekend-day, a different time-polynomial $PO(t)$. To account for this, dummy variables are introduced which activate the relevant time-polynomial and deactivate all other polynomials. The dummy variables $\delta_{Jan} \dots \delta_{Dec}$ represent the months and δ_{WE} / δ_{WD} weekend-days or weekdays, respectively. The regression parameters β_k in the following model are estimated on the basis of the input dataset.

$$\begin{aligned} P = {} & \beta_0 + \beta_1 temperature_{Zur} + \beta_2 temperature_{Zur}^4 + \beta_3 I_G \\ & + \delta_{Jan}\delta_{WD} \sum_{k=4}^{9} \beta_{k,Jan,WD} PO_{k-4}(t) \\ & \qquad + \delta_{Jan}\delta_{WE} \sum_{k=4}^{9} \beta_{k,Jan,WE} PO_{k-4}(t) \\ & + \cdots \\ & + \delta_{Dec}\delta_{WD} \sum_{k=4}^{9} \beta_{k,Dec,WD} PO_{k-4}(t) \\ & \qquad + \delta_{Dec}\delta_{WE} \sum_{k=4}^{9} \beta_{k,Dec,WE} PO_{k-4}(t) \\ & + error \end{aligned}$$

The temperature-dependence of the load can best be described by a polynomial of fourth degree and the radiation effect (global radiation) by a linear trend.
The polynomials $PO(t)$ describe the daily cycle of the load and satisfy two periodicity-conditions.

- Temperature-value at start of the day equals the value at the end of the day
$$PO(t = 0\ h) = PO(t = 24\ h)$$
- Temperature-gradient at start of the day equals the gradient at the end of the day
$$\frac{d}{dt} PO(t)|_{t=0\ h} = \frac{d}{dt} PO(t)|_{t=24\ h}$$

APPLICATION OF THE MODEL

The Regression Model introduced above forms the basis for several statistical analyses. The results presented in this section are derived from the application of the model on the dataset described at the end of the introduction.
The daily trend adjusted, real as well as fitted values against temperature of the year 2010 are depicted in Figure 4. Trend adjusted means that the daily trend curve (i.e. $PO(t)$) is subtracted from the observations.
As expected, the temperature-dependent load is the smallest while temperatures are mild and the demand for heating as well as cooling is low. The minimum is found at 15.3°C for 2010. When the temperature declines below this 15.3°C, the load increases rather gradually. One degree of temperature decrease at 10°C and at minus 10°C results in an additional load of 1.02 MW and 1.80 MW, respectively. In contrast, a much larger increase in load per degree change in temperature can be observed when the temperatures exceed 20°C. At 25°C the load increases by 4.69 MW/°C and at 30°C already by 9.14

MW/°C.

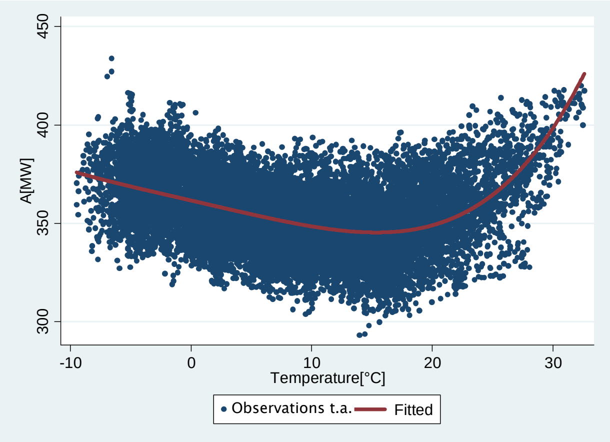

Figure 4: Daily trend adjusted, real as well as fitted values against the temperature of the year 2010

In order to see whether a trend in consumer behaviour can be found, the above model has been applied to the years 2000 to 2010. The fitted load of each year can be seen in Figure 5.

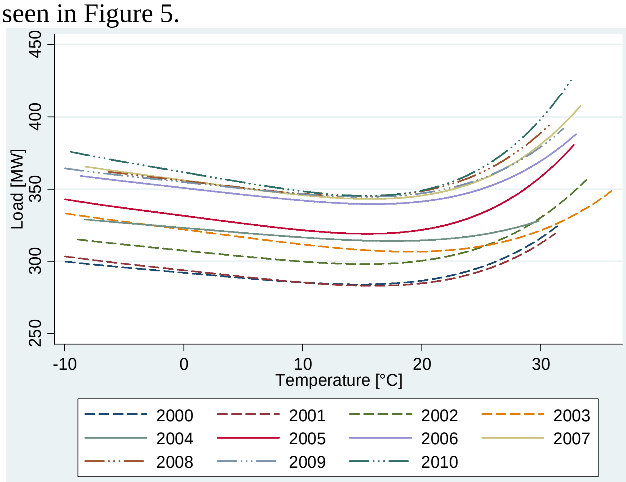

Figure 5: The fitted load for the years 2000 to 2010

Regression model with stagnation point

Surprisingly, the temperature dependency of the load for the range above 15°C is the smallest for the year 2003, the year with the by far warmest summer of the whole sample. For this reason, the residuals for this year were examined more detailed: Whereas the vast majority of the residuals (deviation from the fit) for temperatures above 30°C are negative, the residuals for temperatures between 25°C and 30°C are mainly positive. The year 2003 was, as already mentioned, a year with very high summer temperatures. When temperatures are extremely high, it can be assumed that the load gradually stagnates even if the temperature increases further. This could be linked to the fact that if all of the installed air-conditioners are in operation at full power, the air-conditioners cannot cause any further increase of power consumption even at more extreme temperatures. Consequently, the observed deviation of the residuals is likely to point towards such a stagnation point.

In order to take into account this stagnation, the model from the previous section is modified, so that the load can follow this stagnation for temperatures higher than a certain predefined stagnation temperature, T_{stag}. The model is modified as follows:

$$P = \beta_0 + \beta_1 \, min(temperature, Tstag) + \beta_2 min(abs(temperature), 0°C, T_{stag})^4 + \beta_3 min(abs(temperature), 0°C, T_{stag})^5 + \beta_4 max(temperature, T_{stag}) + \beta_3 \cdot I_G + \cdots$$

$$Constraint: \frac{\partial P}{\partial T_{stag}} = \beta_4 \geq 0$$

β_4 represents the load increase caused by a temperature increase above T_{stag} and is zero for full stagnation. However, in more recent years, especially after 2007, this slope is significantly greater than zero. Hence, β_4 must be allowed to be unequal zero. Another condition to be fulfilled is that the derivative of the load with respect to temperature is continuous. After some testing, the stagnation temperature was found to be 31°C. The temperatures, at which the minimum loads occur, are located very close to each other around 13°C.

In order to allow for better comparison of the load profiles, the fitted loads are expressed in percentage to the respective fitted minimum loads around 13°C and are displayed in Figure 6. The results show a fairly consistent picture. By examining the temperature dependence above the stagnation temperature, it can be seen that stagnation can no longer be observed for the years 2007 to 2010. The load continues to increase above 31°C with 3.5 to 7.5 MW per degree Celsius increase in temperature. It is therefore obvious that the stagnation temperature has moved up in recent years. One reason for this may be newly installed air-conditioning systems, which have a higher capacity and thus, reach their capacity limits at higher temperatures.

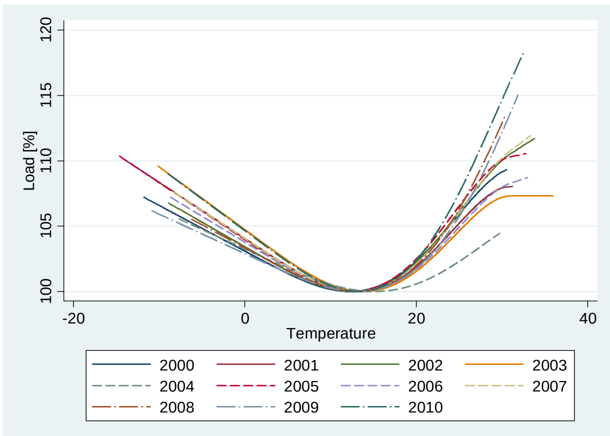

Figure 6: Fitted load in percentage to the fitted minimum load around 13°C of the years 2000 to 2010

To further illustrate the increase of the temperature-dependent load for high temperatures, the fitted relative load at 31°C has been linearly regressed against the years.

$$P(31°C) = \beta_0 + \beta_1 \cdot year$$

This regression shows a significant increase of the relative temperature-dependent load of 0.7% per year (standard deviations in brackets).

$$P(31°C) = \underset{(468.55)}{-1403.00} + \underset{(.234)}{0.705} \cdot year$$

To see how the temperature during future summers might affect the load, the fitted relative temperature-dependent load above 15°C has been extrapolated into the future. Since in a prediction of future developments, the years that are closer to the present are more important than years lying further back in the past, the more recent years were higher weighted. The relative load change per °C increase in temperature relative to the minimum load at 13.16°C can be seen in Figure 7. It is not only shown how a temperature rise during summers might change the load, but also how dramatic the change of the temperature-dependent load has been in the recent years.

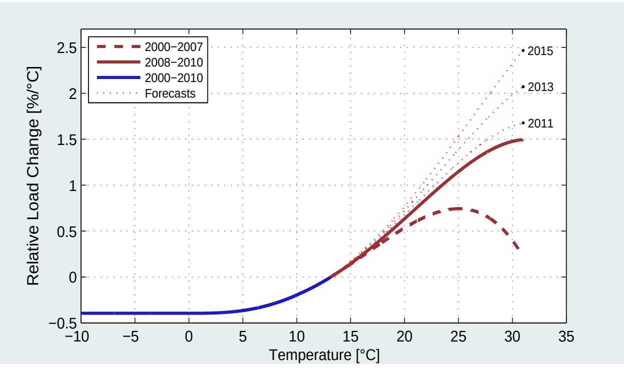

Figure 7: Relative load change per °C increase in temperature by reference to the minimum load around 13°C

SUMMARY AND OUTLOOK

Due to global warming longer periods of elevated temperatures and larger temperature maxima are expected. The former affects mainly energy consumption, the latter the peak load.

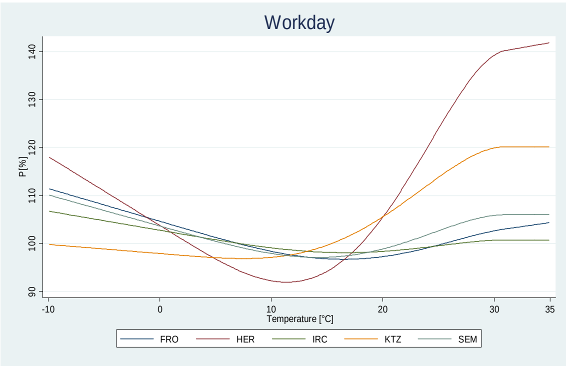

Figure 8: Percentage load of five substations of Zurich against the temperature on weekdays (in relation to the respective average load)

As the study shows, it is important to assess the kind of impact the outside temperature has on electrical power consumption. As a practical application a comparison of five randomly selected substations in the city shows how the temperature dependence of the load can vary per region (Figure 8, 9). In recent years many newly built office and residential high-risers with modern and efficient air-conditioning systems have been added to the supply area of the substation Herdern (HER).

Consequently, the heating- and cooling capacity have increased, the latter primarily on working days.

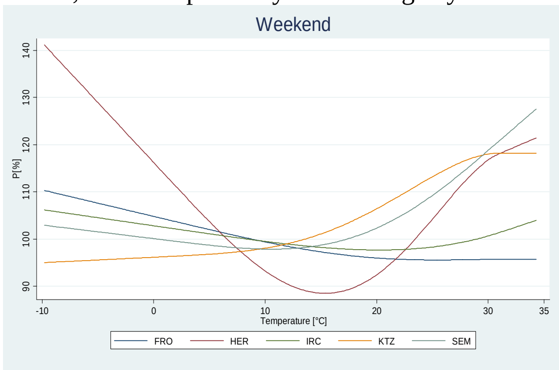

Figure 9: Percentage load of five substations of Zurich against the temperature at weekends (in relation to the respective average load)

For network planning, it is important to know the future change in the entire electrical consumption of the city and its temperature dependence. It is equally important, however, to know this on a local level for each sub-station supply area. Therefore it is planned in continuation of this work to use more detailed load models, which means:

- Classification of individual loads, especially cooling and heating systems (air-conditioners, heat pumps, etc.) according to criteria such as power consumption
- Building mean load curve profiles for these classes and defining their temperature dependence
- Creating statistics for each supply area and load-class
- Improving the load forecast by forecasting the trends for these classes

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