

Preliminary version – to appear as Kiel Working Paper | May 2009

The Impact of Temperature Changes on Residential Energy Consumption

Sebastian Petrick, Katrin Rehdanz and Richard S. J. Tol

Abstract:

To investigate the link between rising global temperature and global energy use, we estimate an energy demand model that is driven by temperature changes, prices and income. The estimation is based on an unbalanced panel of more than 70 countries all over the world over three decades from the mid 1970s. We concentrate on the residential sector only and distinguish four different fuel types (oil, natural gas, coal and electricity). Compared to previous papers, we have a better geographical coverage and consider non-linearities in the impact of temperature on energy demand. We find that energy use is driven by a non-linear heating effect: Energy use not only decreases with a temperature rise due to a reduced demand for energy for heating purposes, but the speed of that decrease declines with a rising temperature level. Furthermore we find evidence that the temperature elasticity of energy is not only affected by the temperature level, but also by the level of income, fuel price and prices of selected substitutes.

Keywords: Energy demand, temperature, heating and cooling effect

JEL classification: Q41, Q43

Sebastian Petrick

Kiel Institute for the World Economy
24100 Kiel, Germany
Telephone: +49 431 8814 263
E-mail: sebastian.petrick@ifw-kiel.de

Katrin Rehdanz

Kiel Institute for the World Economy
Department of Economics, Kiel University, Kiel, Germany

Richard S. J. Tol

Economic and Social Research Institute, Dublin, Ireland
Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands
Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands

The responsibility for the contents of the working papers rests with the authors, not the Institute. Since working papers are of a preliminary nature, it may be useful to contact the author of a particular working paper about results or caveats before referring to, or quoting, a paper. Any comments on working papers should be sent directly to the authors.

1. Introduction

Among the diverse consequences of climate change, a significant rise in global average temperature would be one of the severest, affecting global economies in various ways. One transmission channel of temperature changes is via the energy system of economies. The impact of warming on energy consumption is of particular importance, because it is likely to be a large component of the total economic impact of climate change (Tol 2009). Furthermore, greenhouse gases emitted by the energy sector are themselves a main driver of climate change and responsible for a good quarter of global greenhouse gas emissions (IPCC 2007). Energy consumption thus affects and is affected by both climate change as well as climate policy. To disentangle the impact of temperature changes on energy consumption is the aim of this paper.

So far, most contributions addressed the topic on a micro-level, concentrating on specific sectors of specific countries (Quayle and Diaz 1979; Li and Sailor 1995; Rosenthal and Gruenspecht 1995; Al-Zayer and Al-Ibrahim 1996; Henley and Peirson 1997, 1998; Florides et al. 2000; Vaage 2000, Hunt et al. 2003; Zarnikau 2003; Mirasgedis et al. 2004; Amato et al. 2005; Giannakopoulos et al. 2005; Mansur et al. 2005; Pezzulli et al. 2006; Asadoorian et al. 2007; Mansur et al. 2007). Studies on many countries are few, including those of Bigano et al. (2006) and of Bessec and Fouquau (2008). Bigano et al. (2006) investigate the energy consumption of the residential, industrial and service sectors of up to 26 OECD countries, distinguishing between five different fuel types. They find significant impacts of temperature only for residential energy demand. Energy use of the industrial and service sectors are not significantly influenced by temperature changes. Bessec and Fouquau (2008) focus on total electricity use in the EU-15 and do not differentiate between specific sectors. By applying a smooth threshold regression model they give evidence of existing non-linearities in the link between energy use and temperature. Furthermore they find that the non-linear pattern is more pronounced in warm countries. The only study with a global scope – in the sense that it covers a heterogeneous group of countries all over the world – is by De Cian et al. (2007). They restrict their analysis to the residential sector but include 31 OECD and five non-OECD countries, covering a wider variety of development levels and climate zones than previous studies. They conclude that demand for heating and cooling and its reactions on temperature changes depend on region, season and fuel type.

In this paper, we further extend the analysis of De Cian et al. (2007). First, we add more countries to the sample. This should increase confidence in the estimated relationships, not only because we have more observations, but also because we measure the effects over a wider range of incomes and temperature. Second, we allow for non-linear responses. Winter heating is one example. One would expect less demand for winter heating in warmer countries, but heating demand goes to zero if winters are warm enough. Air conditioning varies from an extravagance to a necessity depending on summer heat. Energy is a luxury good at the lowest incomes and a saturated necessary good at the highest incomes. There is therefore no reason to assume a simple, linear relationship between energy use on the one hand, and climate and income on the other.

The paper is build up as follows: Section 2 gives an overview over the variables we are using to explain energy use, how they affect it and what the intuition behind their effect is. We present the data in section 3 and our findings in section 4. Section 5 concludes our paper and summarizes the main outcomes.

2. Determinants of residential energy consumption

Our study covers the use of different fuel types in the residential sector, namely electricity, solid fuels (excluding biomass, so mainly coal), natural gas, and oil (particularly light fuel oil). We include only the residential sector because previous studies confirmed that energy use in the services and manufacturing sectors reacts only minimally to temperature variations; see Bigano et al. (2006) for a discussion on that point. In our model, households adapt their use of energy to changes in income, fuel prices and temperature. The role of income, the price of the fuel, and the price of other fuels is clear from microeconomic household theory: for the time being, we assume that energy fuels are normal and ordinary goods with positive income elasticity, negative price elasticity and zero or positive cross price elasticity towards other energy fuels.

We also include temperature variables. With rising temperature, households will heat less, whereas the demand for cooling will rise – while the heating effect reduces energy consumption, the cooling effect increases it in the course of a temperature rise. A vital question is the nature of the interdependence between temperature changes and adjustments in the consumption of energy. The usage of a linear model is rather counterintuitive.¹ One would expect that the impact of temperature changes differs substantially depending on the temperature level of the individual country or region. Presumably, during a temperature rise, the effect of a decreased use of energy for heating purposes will be smaller for warmer countries than for relatively colder ones, whereas the energy demand for cooling devices should be larger. The same holds within a country for warmer or colder periods of time.² The introduction of heating (HDD) and cooling degree days (CDD),³ as for example in Al-Zayer and Al-Ibrahim (1996), Amato et al. (2005) or Bigano et al. (2006), already presents a transformation of temperature data that is intended to cover this non-linearity. However, degree days do not provide a smooth adaption of the temperature elasticities to the respective prevailing temperature, but simply introduce a discontinuous jump at a (usually more or less arbitrarily chosen) threshold value. The same problem occurs with the approach of De Cian et al. (2007). Instead of using degree days, they cluster their sample of countries into three groups (hot, temperate and cold countries), for each of which a separate (linear) energy demand equation is estimated. Although these approaches roughly assess non-linearities in the reaction to temperature changes, a more elegant and possibly more realistic treatment would be provided by a non-linear estimation of one demand equation for the whole sample, as is done here.

¹ See for example Bigano et al. (2006), who identify the use of a linear model as a major drawback of their analysis – although strictly speaking they applied a non-linear transformation to their temperature data using heating degree days, as is explained below.

² Since the specific process of the adaptation of energy use in the course of changes in temperature depends on local conditions like insulation, heating and cooling equipment, local conventions etc., the link between temperature and energy use may of course be linear on a small scale, e.g. for a country that is located in only one climate zone. Here, variation in yearly average temperatures is limited. On a global scale however, where variation among average temperatures is higher, a non-linear relationship is much likelier. The question concerning the interpretation of the results derived for the global scale is of course, whether patterns derived from comparisons between countries also hold within a country, given that temperatures rise significantly in the future.

³ Heating degree days are usually defined as the difference between the average temperature of a period and an arbitrary threshold temperature (the *heating threshold*), multiplied with the number of days within that period if the average temperature is below the heating threshold and zero if the average temperature is above (e.g. EUROSTAT 2008). Cooling degree days are the difference between an arbitrary *cooling threshold* and the average temperature of the period, also multiplied with the number of days if the average temperature is above the threshold and zero if it is below.

To cover the non-linearities in the reaction of energy consumption to temperature changes, we introduce non-linear regression equations for each of the four fuel types. As a first step in the direction of accounting for non-linearities, we use linearizable functions to avoid unnecessary complexity and to facilitate the estimation as well as the interpretation of results. We consider different functional forms including polynomials up to third order as well as logarithmic and inverse functions. We also try exponential functions, thereby implying a multiplicative composition of the explanatory variables. Admittedly, this limits comparability and is not very suggestive from an interpretation point of view as long as heating and cooling effects are combined. However, if the latter is not the case, as it should be at least in the case of coal, gas and oil, which are supposedly not used for cooling, we feel that an analysis would be incomplete without including an exponential function. The temperature variables we use to differentiate between the heating and cooling effect are the daily mean temperatures of the hottest and coldest months during one year in each country.

In the short run, the speed of the adjustment of energy use to changes in the explanatory variables is rather limited since it is then mostly restricted to behavioural changes. Extensive adjustment is only possible in the long run and implies changes e.g. in the prevailing and available technical equipment or governmental policy. To account for these inertia, we include the energy use of the preceding period into the equation. Thus, implicitly the whole history of the exogenous variables is taken into account. Including higher lags would mean disregarding too many observations and was thus not considered.

The whole model can be summarized as

$$e_{i,t} = f(\text{tmin}_{i,t}, \text{tmax}_{i,t}, y_{i,t}, pe_{i,t}, ps_{i,t}, e_{i,t-1}, \delta_i),$$

where $e_{i,t}$ is county i 's per-capita consumption of fuel e in year t , $\text{tmin}_{i,t}$ is the daily mean temperature of the coldest, $\text{tmax}_{i,t}$ daily mean temperature of the hottest month in one year, $y_{i,t}$ denotes per-capita income, $pe_{i,t}$ is fuel e 's price, $ps_{i,t}$ is the cross price (possibly a price vector) of substitutable fuels and δ_i are a set of country specific effects. At this stage, the functional form is not yet specified. In the following, we will compare different functional forms, namely linear, quadratic and cubic polynomials as well as logarithmic, inverse and exponential functions. The different functional forms are summarized in table 1.

Table 1: Different functional forms of the regression equation

$$\begin{aligned} \text{Linear:} \quad e_{i,t} &= \alpha \text{tmin}_{i,t} + \beta \text{tmax}_{i,t} + \gamma_1 y_{i,t} + \gamma_2 pe_{i,t} + \gamma_3 ps_{i,t} + \gamma_4 e_{i,t-1} + \delta_i \\ \text{Quadratic:} \quad e_{i,t} &= \sum_{p=1}^2 \alpha_p \text{tmin}_{i,t}^p + \sum_{p=1}^2 \beta_p \text{tmax}_{i,t}^p + \gamma_1 y_{i,t} + \gamma_2 pe_{i,t} + \gamma_3 ps_{i,t} + \gamma_4 e_{i,t-1} + \delta_i \\ \text{Cubic:} \quad e_{i,t} &= \sum_{p=1}^3 \alpha_p \text{tmin}_{i,t}^p + \sum_{p=1}^3 \beta_p \text{tmax}_{i,t}^p + \gamma_1 y_{i,t} + \gamma_2 pe_{i,t} + \gamma_3 ps_{i,t} + \gamma_4 e_{i,t-1} + \delta_i \\ \text{Logarithmic:} \quad e_{i,t} &= \alpha \ln(\text{tmin}_{i,t}) + \beta \ln(\text{tmax}_{i,t}) + \gamma_1 y_{i,t} + \gamma_2 pe_{i,t} + \gamma_3 ps_{i,t} + \gamma_4 e_{i,t-1} + \delta_i^a \\ \text{Inverse:} \quad e_{i,t} &= \alpha (\text{tmin}_{i,t})^{-1} + \beta (\text{tmax}_{i,t})^{-1} + \gamma_1 y_{i,t} + \gamma_2 pe_{i,t} + \gamma_3 ps_{i,t} + \gamma_4 e_{i,t-1} + \delta_i \\ \text{Exponential:} \quad e_{i,t} &= c \cdot \exp(\alpha \text{tmin}_{i,t}) \cdot \exp(\gamma_1 y_{i,t}) \cdot \exp(\gamma_2 pe_{i,t}) \cdot \exp(\gamma_3 ps_{i,t}) \cdot e_{i,t-1} \cdot \delta_i \end{aligned}$$

a: For the logarithmic function, tmin and tmax were added to 20 to prevent loss of observations when taking logarithm of negative temperatures.

3. The data

We use data on the annual average temperature derived from monthly data taken from the High Resolution Gridded Dataset of the Climatic Research Unit of the University of East Anglia (Mitchell et al. 2004). The temperature data are area weighted. Temperature data are available for basically all countries and periods of interest.

Data on energy consumption, prices and real GDP are retrieved from ENERDATA (2005). We distinguish between four major fuel types, viz. oil, gas, solid fuels (coal) and electricity. Sample sizes differ considerably with respect to the different fuel types – both regarding consumption and price data, see table 2 for details. While coal and gas data are available for more than 70 countries, there are time series for almost every country in the world in the case oil and electricity. Compared to this, data on prices are scarce. Price data are available mostly for developed countries, preventing a really globally representative sample of countries if price data are included. Furthermore, reliable price data are available only from 1978 onwards, limiting the estimation sample to this period at most. There are observations on the price of coal for residential consumption for only 22 countries. Even though the share of coal in residential energy demand is usually of minor (and diminishing) importance, this constitutes a shortcoming of the analysis. Unfortunately it was impossible to approximate the price of residential coal by other prices, e.g. coal prices from other sectors. Data availability is better for the prices of other fuel types, where more than 30 countries are covered in the cases of natural gas and light fuel oil prices and 63 countries in the case of electricity prices. Nonetheless, also for those fuel types data limitations impose a considerable drawback of the analysis in terms of representativeness, reliability and quality of the estimation results. As a proxy for household income we use per-capita GDP in purchasing power parities (with respect to 1995 US-Dollars). Compared with energy price and consumption variables, data availability is good.

TABLE 2 ABOUT HERE

4. Results

The effect of temperature changes on residential energy consumption is quite different with respect to the individual fuels. The most fundamental distinction is the one between electricity on the one hand and coal, gas and oil on the other, because the latter are more or less exclusively used for heating purposes in the residential sector whereas electricity is used for a range of services, including heating and cooling but also services that are less sensitive to climate and weather, such as lighting.⁴

Tables 3 to 5 summarize the regression results for oil, gas and coal. The tables report the parameters and p-values of the explanatory variables resulting from an estimation using the generalized method of moments estimator for dynamic panels proposed by Arellano and Bond (1991). For all three fuels, we find a highly significant heating effect. The existence of a cooling effect was tested (not reported here) and could be rejected irrespective of the functional form. In terms of significance of the parameters, a linear as well as a logarithmic or an exponential heating effect can be supported for all three fuels.

⁴ Of course it is possible that households use their own generator to produce electricity from oil products themselves. The cooling effect could then also affect the consumption of oil. Apart from the fact that this effect is supposedly only of minor importance, most of it is statistically covered by the transport sector and not by the household sector anyway, which leaves it beyond the scope of this study.

TABLES 3 TO 5 ABOUT HERE

The size and significance of the heating effect are largely unaffected by the inclusion of the price of the three other fuels. The same is true for the income and price elasticities. While oil shows no significant reaction on income changes, the consumption of natural gas exhibits a positive income elasticity. A special case in that respect is coal. Though not significant in the case of a linear or logarithmic specification, the exponential specification (as the logarithmic without cross prices) reveals a negative impact of per-capita GDP on coal consumptions. That is, coal is an inferior good, a finding that is in line with previous evidence.

In general, cross-price elasticities are small and insignificant. While all three specifications concordantly state that consumption of oil does not depend on the prices of coal and gas, they differ with respect to coal and gas. For coal, the linear and logarithmic specification display a positive influence of the prices of gas and oil at the 10% significance level, indicating the substitutability of coal. The exponential specification displays a small but significant negative influence of the electricity price on coal consumption. For the case of natural gas, especially the role of the oil price is of interest, since this interrelation is well established in the literature (see e.g. Bigano et al. 2006). Both the linear and the exponential approach show a positive cross price elasticity. The linear approach additionally gives a significant positive parameter of the electricity price, as does the logarithmic approach.

To assess the three different functional forms, we evaluate the adjusted R^2 .⁵ Since the adjusted R^2 is generally very high due to the included autoregressive term, already small differences in the adjusted R^2 give evidence of the specification's ranking with respect to degree of explanation. It turns out that for oil, gas and coal the linear specification is inferior towards the logarithmic or exponential one. Thus the hypothesis of a linear heating effect on oil, gas or coal can be rejected in favour of a logistic or exponential one.

Whether the logistic or the exponential specification is the right one is not merely a question of fit or significance of parameters – in fact the trend of both functions for given values of the control variables is not so different. It is more a question of the correct theoretic model. While the elasticities of both approaches are decreasing with rising temperatures, and are also of decreasing slope, for the exponential specification the impact of temperature depends not only on temperature itself, but also on the other explanatory variables, namely income, price and cross prices. For the logistic specification, the impact of temperature on energy consumption depends only on temperature itself. The question now is: are such dependencies of the heating effect on the income or price level plausible or not. We think that that is the case. Households with higher income have more options to react to temperature changes than low-income households have (e.g. by improving insulation or heating systems); the same argument holds for the comparison between high and low income countries. Thus the decrease of energy consumption in the course of a temperature rise should be steeper, if the country is comparably richer. On the other hand, households with comparably low income have more incentives to put into effect the possible gains from possible energy savings, simply as this would increase their disposable income. In any case, the income level has an effect on the temperature elasticity of energy demand. Analogous reasoning is true for different price levels: The higher the price level is, the more willing a household (or country) will be to react on a temperature changes because the impact on its income is higher. So price changes will

⁵ The Arellano Bond estimator we apply estimates the model in differences and prevents the direct computation of the sum of squared residuals or any derived measure for the levels equation from the estimation output. Therefore we calculated the adjusted R^2 from the predicted values of the dependent variable.

influence the reaction on temperature changes as well. Nevertheless, the different direct and indirect effects of income as well as prices on energy consumption partly counteract each other, which makes it impossible to identify the individual effects in the parameters of our models.

So far, we have concentrated on oil, natural gas and coal. The case of electricity is more difficult, because temperature changes affect electricity consumption not only via the heating effect, but also through the cooling effect: More or less all cooling appliances such as air conditioning or refrigerators are run by electricity. However, as tables 6 and 7 illustrate, the evidence of the cooling effect in our data is limited. Only the logarithmic and inverse functions display an effect of changing cooling temperatures at all, and in these cases in the same (negative) direction as the heating effect. Does that mean that there is no cooling effect, or even a negative one? Not necessarily. The dataset we are using has two drawbacks when it comes to extracting the cooling effect. First, the geographical scope of the data set is broad, it includes developed as well as many developing countries. So far on the macro scale, the cooling effect has been derived mainly for developed countries (De Cian et al. 2007 for example cover the OECD countries and in addition South Africa, India, Thailand and Venezuela; Bessec and Fouquau 2008 cover the EU-15 countries). However, the structure in developing countries will be quite different when it comes to reacting to temperature changes. Although most developing countries are located in warm regions, the endowment with air conditioning and other cooling devices is supposedly below average since the households' incomes are below average as well. Again, we supposedly have a multiplicative link between temperature elasticity and income. In this case, however, this link is much more difficult to be represented in an estimation equation: As electricity is used for heating and cooling, an exponential function that covers both minimum and maximum temperature would also link the two temperature variables in a multiplicative way, which is rather counterintuitive. However, beyond this general objection, our data prevent identifying the cooling effect also for a second reason that results partly from the choice of proxies for the heating and cooling effect. The minimum and maximum temperature of a country is highly correlated, leading to a high degree of multicollinearity as soon as both variables are included in the estimation equation. This does no harm in terms of biasedness or inefficiency of the estimator but leads to higher variances of the estimated parameters, leading to excessively low levels of parameter significance. Thus, as long as both temperature variables are included in the model, the impact of the maximum temperature is either neglected or simply reproduces the heating effect.

TABLES 6 AND 7 ABOUT HERE

As long as only the heating effect is considered, the squared and again the logarithmic and exponential specifications yield the best results in terms of significance of parameters and fit.⁶ A linear heating effect can again be rejected. All three specifications report only a small income elasticity, if any – income elasticity never exceeds 0.1. The price elasticity of electricity can be neglected as well, only the exponential specification displays a significant, though small influence. The influence of gas is of adequate certainty but also of small size. For the question whether the squared, logarithmic or exponential function is most appropriate the same argument as in the case of the other fuels hold. As long as only one temperature variable is included in the specification, the multiplicative link provided by the exponential function reflects real-world conditions most realistically. If interlinkages between the control variables and the heating (or, if verified, cooling) effect shall not be emphasized, the more

⁶ Alternative specifications reflecting different natures of heating and cooling effect were considered as well, but did not lead to more meaningful results and are thus not reported.

simple logarithmic and in the case of electricity also the squared specification should be considered.

5. Conclusion

In this paper we have examined the impact of temperature changes on residential energy consumption, emphasizing the evaluation of different functional forms of that impact. It becomes clear that energy use is driven by a non-linear heating effect: Energy use not only drops in the course of a temperature rise due to a reduced demand for energy for heating purposes, but the speed of that drop declines with a rising temperature level. Furthermore we found evidence that the size of the heating effect is not only affected by the temperature level, but also by the level of income, fuel price and prices of selected substitutes. The geographical scope of our paper is considerably larger than in previous studies, and covers both developed and developing countries. This broad geographical scope allows us to form conclusions of general validity. However, this generality necessarily involves a loss of provision for specific circumstances: For example, we are not able to identify a cooling effect of worldwide impact, a result that only partly reflects the true circumstances but is partly owing to restrictions regarding the highly collinear temperature data. These shortcomings add to the general caveats regarding detailed statistical data from developing countries.

Considering different economic sectors, especially industry and services, would be a natural extension of this study. Even if the residential sector is the one with the highest sensitivity towards temperature changes with respect to energy demand, similar effects should be in effect for other sectors as well. Extending the analysis to more fuel types could be a sensible extension. Especially the consideration of biomass would lead to a more complete picture of the interrelations in developing countries, since a considerable fraction of residential energy consumption falls upon fire wood and other biomass-based fuels. A more methodological extension would be the use of explicitly non-linear estimators instead of linearizable non-linear functions. This is left for further research as well as a closer inspection of interdependences between the control variables and the heating and cooling effect.

Acknowledgements

The Cluster of Excellence “The Future Ocean” provided welcome financial support. All errors and opinions are ours.

References

- Al-Zayer, J. and A. A. Al-Ibrahim (1996): *Modelling the Impact of Temperature on Electricity Consumption in the Eastern Province of Saudi Arabia*. *Journal of Forecasting* 15, pp. 97-106.
- Amato, A. D., M. Ruth, P. Kirshen and J. Horwitz (2005): *Regional Energy Demand Responses to Climate Change: Methodology and Application to the Commonwealth of Massachusetts*. *Climatic Change* 71, pp. 175-201.
- Arellano, M and S. Bond (1991): *Some Tests of Specification for Panel Data: Monte Carlo Evidence and an Application to Employment Equations*. *Review of Economic Sciences* 58, pp. 277-297.
- Asadoorian, M. O., R. S. Eckaus and C. A. Schlosser (2007): *Modelling Climate Feedbacks to Electricity Demand: The Case of China*. *Energy Economics* 30, pp. 1577-1602.

- Bessec, M. and J. Fouquau (2008): *The non-linear link between electricity consumption and temperature in Europe: A threshold panel approach*. Energy Economics 30, pp. 2705-2721.
- Bigano, A., F. Bosello and G. Marano (2006): *Energy demand and Temperature: A Dynamic Panel Analysis*. FEEM Nota Di Lavoro 112.2006.
- De Cian, E., E. Lanzi and R. Roson (2007): *The Impact of Temperature Change on Energy Demand: A Dynamic Panel Analysis*. FEEM Nota Di Lavoro 46.2007.
- ENERDATA (2005): Multiple Databases on Energy Consumption, Energy Prices and Other Indicators. More Information on <http://www.enerdata.fr/enerdatauk/eshop/index.php>.
- EUROSTAT (2008): *Heating Degree-days. Eurostat Metadata in SDDS format: Summary Methodology*. Download from http://epp.eurostat.ec.europa.eu/cache/ITY_SDDS/EN/nrg_esdgr_sm1.htm (2009-02-03).
- Florides, G. A., S. A. Kalogirou, S. A. Tassou and L. C. Wrobel (2000): *Modelling of the Modern Houses of Cyprus and Energy Consumption Analysis*. Energy 25, pp. 915-937.
- Giannakopoulos, C., B. E. Psiloglou and S. Majithia (2005): *Weather and Non-weather Related Factors Affecting Energy Load Demand: A Comparison of the Two Cases of Greece and England*. Geophysical Research Abstracts 7,06969. Download from <http://www.cosis.net/abstracts/EGU05/06969/EGU05-J-06969.pdf> (2009-02-02).
- Henley, A. and J. Peirson (1997): *Non-Linearities in Electricity Demand and Temperature: Parametric versus Non-parametric Methods*. Oxford Bulletin of Economics and Statistics, 59,1, pp. 149-162.
- Henley, A. and J. Peirson (1998): *Residential energy demand and the interaction of price and temperature: British experimental evidence*. Energy Economics 20, pp. 157-171.
- Hunt, L.C., G. Judge and Y. Ninomiya (2003): *Modelling Underlying Energy Demand Trends*. Surrey Energy Economics Discussion paper Series (SEEDS) 105.
- IPCC (2007): *4th Assessment Report "Climate Change 2007: Synthesis Report"*. Download from <http://www.ipcc.ch/ipccreports/ar4-syr.htm> (2008-11-24).
- Li, X. and D. J. Sailor (1995): *Electricity use sensitivity to climate and climate change*. World Resource Review 7(3), pp. 334-446.
- Mansur, E. T., R. Mendelsohn and W. Morrison (2005): *A Discrete-Continuous Choice Model of Climate Change Impacts on Energy*. Yale School of Management Working Paper ES-43.
- Mansur, E. T., R. Mendelsohn and W. Morrison (2008): *Climate Change Adaptation: A Study of Fuel Choice and Consumption in the U.S. Energy Sector*. Journal of Environmental Economics and Management 55(2), pp. 175-193.
- Mirasgedis, S., Y. Sarafidis, E. Georgopoulou, D. P. Lalas, M. Moschovits, F. Karagiannis, D. Papakonstantinou (2004): *Models for mid-term electricity demand forecasting incorporating weather influences*. Energy 31, pp. 208-227.
- Mitchell, T. D., T. R. Carter, P. D. Jones, M. Hulme and M. New (2004): *A comprehensive set of high-resolution grids of monthly climate for Europe and the globe: the observed record (1901–2000) and 16 scenarios (2001–2100)*. Tyndall Centre Working Paper 55.
- Pezzulli, S., P. Frederic, S. Majithia, S. Sabbagh, E. Black, R. Sutton and D. Stevenson (2006): *The seasonal forecast of electricity demand: A hierarchical Bayesian model with climatological weather generator*. Applied Stochastic Models in Business and Industry 22, pp. 113-125.
- Quayle, R. G. and H. F. Diaz (1978): *Heating Degree Day Data Applied to Residential Heating and Energy Consumption*. Journal of Applied Meteorology 19, pp. 241-246.
- Rosenthal, D. H. and H. K. Gruenspecht (1995): *Effects of global warming on energy use for space heating and cooling in the United States*. Energy Journal 16, pp. 77-97.

- Tol, R. S. J. (2009): *The economic effect of climate change*. Journal of Economic Perspectives 23(2), pp. 29-51.
- Vaage, K. (2000): *Heating technology and energy use: A discrete continuous choice approach to Norwegian household energy demand*. Energy Economics 22, pp. 649-666.
- Zarnikau, J. (2003): *Functional forms in energy demand modelling*. Energy Economics 25, pp. 603-613.

Tables

Table 2: Descriptive statistics

| Variable | Mean | Std. Dev. | Min | Max | Included Observations | | |
|---|----------|-----------|--------|----------|-----------------------|-----|----|
| | | | | | N | n | T |
| Consumption per capita (toe) | | | | | | | |
| Electricity | 56.93 | 98.02 | 0.15 | 692.71 | 4 290 | 176 | 24 |
| Light fuel oil | 65.88 | 127.73 | 0.03 | 1 170.27 | 4 351 | 174 | 25 |
| Gas | 90.29 | 140.66 | 0.00 | 806.86 | 1 580 | 72 | 22 |
| Solid fuels | 44.25 | 87.33 | 0.00 | 632.49 | 1 346 | 69 | 20 |
| Price for residential sector (PPP(95USD) per toe) | | | | | | | |
| Electricity | 1 329.18 | 1 014.09 | 40.45 | 8 835.40 | 1 029 | 63 | 16 |
| Light fuel oil | 412.79 | 189.57 | 112.36 | 1 352.68 | 662 | 33 | 20 |
| Gas | 429.12 | 233.04 | 5.10 | 1 300.17 | 614 | 38 | 16 |
| Coal | 163.53 | 65.03 | 13.38 | 305.23 | 308 | 22 | 14 |
| GDP per capita (PPP(95USD)) | 6.68 | 6.82 | 0.42 | 43.94 | 4 265 | 162 | 26 |
| Daily average temperature in the coldest month (°C) | 10.75 | 8.11 | -12.2 | 23.95 | 2 190 | 73 | 30 |
| Daily average temperature in the hottest month (°C) | 20.48 | 8.74 | -2.6 | 32.9 | 2 190 | 73 | 30 |

N: Total number of observations; n: Number of countries with at least one observation; T: Average number of periods per country.

Table 3: Estimation results for residential consumption of oil products

| | cubic | squared | linear | logarithmic | inverse | exponential | including cross prices | | |
|------------------------------|-------------------|-------------------|-------------------|-------------------|------------------|------------------|------------------------|-------------------|-----------------|
| | | | | | | | linear | logarithmic | exponential |
| oil use in (t-1) | 0.84*** 0.00 | 0.84*** 0.00 | 0.84*** 0.00 | 0.80*** 0.00 | 0.85*** 0.00 | 0.83*** 0.00 | 0.72*** 0.00 | 0.73*** 0.00 | 0.79*** 0.00 |
| tmin | -17.64*** 0.00 | -16.21*** 0.00 | -15.81*** 0.00 | | | -0.05*** 0.00 | -21.50*** 0.00 | | -0.05** 0.03 |
| tmin ² | -0.04 0.81 | 0.07 0.58 | | | | | | | |
| tmin ³ | 0.02 0.16 | | | | | | | | |
| log(tmin) | | | | -73.66*** 0.00 | | | | -72.13*** 0.01 | |
| tmin ⁻¹ | | | | | 1.61 0.23 | | | | |
| GDP (per capita) | 0.61 0.40 | 0.56 0.45 | 0.56 0.46 | 0.46 0.57 | -0.98 0.15 | 0.00 1.00 | 0.75 0.57 | 0.15 0.90 | 0.00 0.99 |
| Oil price | -0.07*** 0.00 | -0.07*** 0.00 | -0.07*** 0.00 | -0.07** 0.02 | -0.07** 0.01 | -0.00*** 0.00 | -0.06 0.06 | -0.07** 0.04 | -0.00** 0.05 |
| Electricity price | | | | | | | -0.01 0.59 | -0.01 0.57 | 0.00 0.55 |
| Coal price | | | | | | | -0.07 0.50 | -0.07 0.56 | 0.00 0.31 |
| Gas price | | | | | | | 0.00 0.98 | 0.00 0.97 | 0.00 0.55 |
| Constant | 135.38*** 0.00 | 138.38*** 0.00 | 141.79*** 0.00 | 188.97*** 0.00 | 65.78*** 0.01 | 1.17*** 0.00 | 210.60*** 0.00 | 223.23*** 0.01 | 1.54*** 0.00 |
| RSS (differences) | 627452.9 | 627829.5 | 629619.3 | 460739.3 | 721296.9 | 24,9 | 259689.9 | 270657.9 | 14,4 |
| R ² adj. (levels) | 0.813 | 0.758 | 0.743 | 0.935 | 0.972 | 0.917 | 0.924 | 0.932 | 0.943 |
| N | 571 | 571 | 571 | 483 | 571 | 571 | 221 | 221 | 221 |

*** significant at 1%, ** significant at 5%, * significant at 10%. p-values below parameters. Since we use the Arellano-Bond estimator, RSS is the sum of squared residuals of the differenced equation. R² adj. is based on estimated levels.

Table 4: Estimation results for residential consumption of natural gas

| | cubic | squared | linear | logarithmic | inverse | exponential | including cross prices | | |
|------------------------------|-------------------|-------------------|-------------------|-------------------|-----------------|------------------|------------------------|-------------------|------------------|
| | | | | | | | linear | logarithmic | exponential |
| gas use in (t-1) | 0.82*** 0.00 | 0.82*** 0.00 | 0.82*** 0.00 | 0.85*** 0.00 | 0.80*** 0.00 | 0.80*** 0.00 | 0.72*** 0.00 | 0.71*** 0.00 | 0.91*** 0.00 |
| tmin | -11.69*** 0.00 | -10.99*** 0.00 | -11.93*** 0.00 | | | -0.05*** 0.00 | -11.67*** 0.00 | | -0.07*** 0.00 |
| tmin ² | -0.18 0.49 | -0.15 0.48 | | | | | | | |
| tmin ³ | 0.01 0.50 | | | | | | | | |
| log(tmin) | | | | -51.41*** 0.00 | | | | -37.51*** 0.00 | |
| tmin ⁻¹ | | | | | 0.25 0.53 | | | | |
| GDP (per capita) | 1.69*** 0.00 | 1.69*** 0.00 | 1.66*** 0.00 | 1.16** 0.00 | 0.51 0.42 | 0.01* 0.03 | 2.02** 0.00 | 1.72** 0.00 | 0.00 0.41 |
| Gas price | -0.03** 0.02 | -0.03** 0.02 | -0.03** 0.02 | -0.03** 0.03 | -0.03** 0.04 | 0 0.25 | -0.02 0.27 | -0.02 0.28 | -0.00** 0.01 |
| Electricity price | | | | | | | 0.01* 0.01 | 0.01*** 0.00 | 0.00 0.34 |
| Coal price | | | | | | | -0.08 0.12 | -0.08 0.15 | 0.00 0.80 |
| Oil price | | | | | | | 0.02*** 0.00 | 0.02 0.22 | 0.00* 0.05 |
| Constant | 91.78*** 0.01 | 91.20*** 0.01 | 86.99*** 0.01 | 115.80*** 0.00 | 39.85** 0.02 | 1.06*** 0.00 | 87.42** 0.01 | 94.41*** 0.00 | 0.86*** 0.00 |
| RSS (differences) | 245205.9 | 246220.8 | 247381.6 | 228224.7 | 301834.4 | 21,4 | 97827.8 | 105049.2 | 5,3 |
| R ² adj. (levels) | 0.838 | 0.815 | 0.836 | 0.951 | 0.958 | 0.941 | 0.898 | 0.898 | 0.98 |
| N | 495 | 495 | 495 | 447 | 495 | 495 | 222 | 222 | 222 |

*** significant at 1%, ** significant at 5%, * significant at 10%. p-values below parameters. Since we use the Arellano-Bond estimator, RSS is the sum of squared residuals of the differenced equation. R² adj. is based on estimated levels.

Table 5: Estimation results for residential consumption of coal

| | cubic | squared | linear | logarithmic | inverse | exponential | including cross prices | | |
|------------------------------|-----------------|-----------------|------------------|-------------------|-----------------|------------------|------------------------|------------------|-----------------|
| | | | | | | | linear | logarithmic | exponential |
| coal use in (t-1) | 0.62*** 0 | 0.61*** 0 | 0.60*** 0 | 0.60*** 0 | 0.61*** 0 | 0.74*** 0 | 0.68*** 0 | 0.68*** 0 | 0.81*** 0 |
| tmin | -0.68 0.78 | -0.12 0.97 | -7.05*** 0 | | | -0.09*** 0.01 | -6.04*** 0 | | -0.09** 0.02 |
| tmin ² | -0.53* 0.08 | -0.89* 0.05 | | | | | | | |
| tmin ³ | -0.03 0.55 | | | | | | | | |
| log(tmin) | | | | -24.00*** 0.01 | | | | -19.98** 0.02 | |
| tmin ⁻¹ | | | | | 2.74 0.44 | | | | |
| GDP (per capita) | -2.25 0.11 | -2.24 0.11 | -2.5 0.1 | -2.71* 0.1 | -3.19* 0.07 | -0.05** 0.02 | -0.56 0.47 | -0.75 0.36 | -0.02*** 0 |
| Coal price | 0 0.99 | 0 1 | 0 0.97 | 0.01 0.96 | 0.03 0.77 | 0 0.23 | -0.12 0.18 | -0.12 0.16 | 0 0.11 |
| Electricity price | | | | | | | 0 0.52 | 0 0.52 | -0.00*** 0 |
| Gas price | | | | | | | 0.04* 0.06 | 0.04* 0.06 | 0 0.45 |
| Oil price | | | | | | | 0.02* 0.05 | 0.02* 0.07 | 0 0.19 |
| Constant | 97.26** 0.01 | 96.98** 0.01 | 102.58** 0.01 | 110.66*** 0.01 | 73.56** 0.04 | 2.28*** 0 | 57.75* 0.07 | 62.26* 0.07 | 1.75*** 0 |
| RSS (differences) | 98991.86 | 99055.69 | 101505.71 | 102685.38 | 107179.41 | 24.94 | 80519.89 | 81781.5 | 14.41 |
| R ² adj. (levels) | 0.454 | 0.598 | 0.772 | 0.83 | 0.84 | 0.86 | 0.884 | 0.893 | 0.927 |
| N | 260 | 260 | 260 | 242 | 260 | 260 | 222 | 222 | 222 |

*** significant at 1%, ** significant at 5%, * significant at 10%. p-values below parameters. Since we use the Arellano-Bond estimator, RSS is the sum of squared residuals of the differenced equation. R² adj. is based on estimated levels.

Table 6: Estimation results for residential consumption of electricity (without cross prices)

| | cubic | squared | squared (no cooling) | linear | logarithmic | logarithmic (no cooling) | inverse | inverse (no cooling) | exponential (no cooling) |
|------------------------------|-----------------|------------------|-------------------------|------------------|------------------|-----------------------------|-----------------|-------------------------|-----------------------------|
| electr. use in (t-1) | 0.87*** 0.00 | 0.87*** 0.00 | 0.87*** 0.00 | 0.86*** 0.00 | 0.89*** 0.00 | 0.89*** 0.00 | 0.87*** 0.00 | 0.87*** 0.00 | 0.88*** 0.00 |
| tmin | -3.76** 0.02 | -3.50*** 0.01 | -2.85*** 0.00 | -1.65* 0.06 | | | | | -0.01** 0.01 |
| tmin ² | 0.19* 0.06 | 0.13*** 0.00 | 0.11*** 0.00 | | | | | | |
| tmin ³ | 0.00 0.30 | | | | | | | | |
| log(tmin) | | | | | -2.23 0.29 | -5.57*** 0.00 | | | |
| tmin ⁻¹ | | | | | | | 1.50*** 0.00 | 1.50*** 0.00 | |
| tmax | 2.75 0.54 | 1.08 0.50 | | -0.30 0.44 | | | | | |
| tmax ² | -0.12 0.58 | -0.02 0.49 | | | | | | | |
| tmax ³ | 0.00 0.64 | | | | | | | | |
| log(tmax) | | | | | -11.61** 0.03 | | | | |
| tmax ⁻¹ | | | | | | | 0.48*** 0.00 | | |
| GDP (per capita) | 0.84* 0.06 | 0.84* 0.06 | 0.83* 0.07 | 0.85* 0.07 | 0.55 0.21 | 0.52 0.22 | 0.54 0.13 | 0.59 0.11 | 0.01** 0.04 |
| Electricity price | 0.00 0.25 | 0.00 0.22 | 0.00 0.23 | 0.00 0.22 | 0.00 0.20 | 0.00 0.19 | 0.00 0.16 | 0.00 0.17 | -0.00* 0.09 |
| Constant | 0.94 0.97 | 8.50 0.49 | 15.79*** 0.00 | 25.61*** 0.00 | 42.27*** 0.00 | 15.58*** 0.00 | 8.41** 0.02 | 8.32** 0.02 | 0.55*** 0.00 |
| RSS (differences) | 41 043.0 | 40 998.2 | 40 784.3 | 42 050.9 | 14 002.6 | 14 253.1 | 43 396.8 | 43 177.0 | 4.2 |
| R ² adj. (levels) | 0.991 | 0.991 | 0.991 | 0.987 | 0.992 | 0.994 | 0.983 | 0.982 | 0.989 |
| N | 847 | 847 | 847 | 847 | 758 | 758 | 847 | 847 | 847 |

*** significant at 1%,
 ** significant at 5%,
 * significant at 10%.
 p-values below parameters.
 Since we use the Arellano-Bond estimator, RSS is the sum of squared residuals of the differenced equation.
 R² adj. is based on estimated levels.

Table 7: Estimation results for residential consumption of electricity (including cross prices)

| | including cooling effect | | without cooling effect | | |
|------------------------------|--------------------------|------------------|------------------------|------------------|------------------|
| | squared | logarithmic | squared | logarithmic | exponential |
| electr. use in (t-1) | 0.92*** 0.00 | 0.92*** 0.00 | 0.91*** 0.00 | 0.92*** 0.00 | 0.91*** 0.00 |
| tmin | -3.20*** 0.00 | | -4.31*** 0.00 | | -0.02*** 0.00 |
| tmin ² | 0.16 0.15 | | 0.20 0.13 | | |
| log(tmin) | | -6.72*** 0.00 | | -9.39*** 0.00 | |
| tmax | -3.05 0.20 | | | | |
| tmax ² | 0.09 0.27 | | | | |
| log(tmax) | | -9.82* 0.05 | | | |
| GDP (per capita) | -0.05 0.84 | -0.05 0.84 | 0.00 0.99 | -0.04 0.86 | 0.00 0.55 |
| Electricity price | 0.00 0.55 | 0.00 0.43 | 0.00 0.35 | 0.00 0.35 | -0.00** 0.02 |
| Coal price | 0.00 0.75 | 0.00 0.78 | 0.00 0.90 | 0.00 0.80 | 0.00 0.56 |
| Gas price | -0.01** 0.01 | -0.01** 0.02 | -0.01** 0.01 | -0.01** 0.01 | -0.00** 0.02 |
| Oil price | -0.00* 0.10 | -0.00* 0.09 | 0.00 0.16 | 0.00 0.10 | 0.00 0.14 |
| Constant | 57.18*** 0.00 | 57.47*** 0.00 | 38.19*** 0.00 | 37.40*** 0.00 | 0.63*** 0.00 |
| RSS (differences) | 6 216.8 | 6 194.5 | 6 308.9 | 6 326.5 | 0.5 |
| R ² adj. (levels) | 0.978 | 0.979 | 0.977 | 0.978 | 0.989 |
| N | 222 | 222 | 222 | 222 | 222 |

*** significant at 1%, ** significant at 5%, * significant at 10%. p-values below parameters. Since we use the Arellano-Bond estimator, RSS is the sum of squared residuals of the differenced equation. R² adj. is based on estimated levels.